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AN EVALUATION OF TOTAL FLOODING HIGH EXPANSION FOAM FIRE SUPPRESSION SYSTEMS FOR MACHINERY SPACE APPLICATIONS

FINAL REPORT
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16. Abstract (MAXIMUM 200 WORDS)

Full-scale fire tests were conducted to identify the fire extinguishing capabilities and limitations of High Expansion Foam Fire Suppression Systems (HEFFSS) in shipboard machinery space applications. A total of 35 tests were conducted in this evaluation utilizing the equipment and foam concentrates from three manufacturers: Ansul, Buckeye and Chemguard. All three systems easily extinguished the pan fires included in this evaluation independent of the type of fuel (heptane or diesel). The differences in the systems' capabilities were observed during the extinguishment of the heptane spray fires that presented a major challenge to the HEFFSS.

The difficulty observed in extinguishing spray fires and, conversely, the ease in extinguishing the pan fires, demonstrates that the current high expansion foam test protocol (MSC/Circ. 670) is inadequate for approving HEFFSS for machinery space applications. As a result, it is recommended that HEFFSS be approved using a modified version of the gaseous agent test protocol MSC/Circ. 848 rather than MSC/Circ. 670. Recommendations on how to modify the protocol to account for the differences between high expansion foam and gaseous agent technologies are provided in the report as well as issues requiring further research.

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EXECUTIVE SUMMARY

Full-scale fire tests were conducted to identify the fire extinguishing capabilities and limitations of High Expansion Foam Fire Suppression Systems (HEFFSS) in shipboard machinery space applications. The results will be used to assist the United States Coast Guard (USCG) in developing a position on the use of HEFFSS in machinery space applications and in the development of approval standards (i.e., acceptance testing).

There are currently two International Maritime Organization (IMO) test protocols that HEFFSS must meet/pass to be approved for commercial ships. These protocols include a fire test described in Maritime Safety Committee (MSC) circular 670, “Guidelines for the Performance and Testing Criteria and Surveys of High-Expansion Foam Concentrates for Fixed Fire-Extinguishing Systems,” and a chemical compatibility test (compatibility with salt water) in MSC circular 582, “Guidelines for the Performance and Testing Criteria, and Surveys of Low-Expansion Foam Concentrates for Fixed Fire-Fire Extinguishing Systems.” Although the requirements of MSC/Circ. 582 may apply, the test setup, HEFFSS hardware and fire scenario in MSC/Circ. 670 are not in any way representative of the conditions and hazards of a shipboard machinery space.

MSC/Circ. 670 consists of a 1.73 m^2 heptane pan fire conducted in a 2 m x 2 m x 1 m enclosure. The enclosure is made of wire mesh. A specific size (6.1 Lpm at 500 kPa) high expansion foam generator is used to extinguish the fire during the test. There does not appear to be any connection between the foam generator used during the test and those installed on the ship (the ones installed on the ship should have a significantly greater capacity). In order to successfully complete the test, the fire must be extinguished within 120 seconds of system activation.

Since MSC/Circ. 670 is not considered representative of machinery space applications and hazards, the first step was to identify a set of tests in which to evaluate these systems. There are currently four International Maritime Organization (IMO) test methods for approving other technologies for machinery space applications. These include the standard for approving water based (mist) systems (MSC circular 668/728), the gaseous agent test protocol (MSC circular

848), and the fixed aerosol test protocol (MSC circular 1007). After reviewing these standards/protocols, the gaseous agent test protocol (MSC circular 848) was selected to be the basis of this investigation.

MSC circular 848 consists of five tests. The first test is an agent distribution test conducted against small fires located in the corners of the compartment and was not included in this evaluation. The remaining four tests consist of combinations of spray, pan and wood crib fires providing an assessment of the HEFFSS capabilities against a range of fire sizes, types, and locations (elevations and degree of obstruction).

A total of 35 tests were conducted in this evaluation utilizing the equipment and foam concentrates from three manufacturers: Ansul, Buckeye and Chemguard. All three systems easily extinguished the pan fires included in this evaluation independent of the type of fuel (heptane or diesel). The differences in system capabilities were observed during the extinguishment of the spray fires (namely, the heptane spray fires). The heptane spray fires presented a major challenge to the HEFFSS and, in some cases, were not extinguished.

With respect to the individual systems, there were variations in the fire suppression capabilities and/or foam quality between the three manufacturers. The Buckeye and Chemguard systems produced more robust foam and were both capable of extinguishing the heptane spray fires. The foam produced by these two systems was so robust, the space needed to be cleaned using a defoaming agent after each test. The Ansul foam was more fragile and had difficulty extinguishing the heptane spray fires. During cleanup, the Ansul foam was quickly broken down/washed away using short bursts of water. It is unknown whether the difficulty in extinguishing the heptane spray fires was associated with the foam concentrate, foam-generating equipment or both.

The results of these tests demonstrate the potential for using HEFFSS for protecting shipboard machinery spaces. Additional research is required in specific areas to fully understand the capabilities and limitations of these systems. Areas requiring further research include understanding the mechanisms of extinguishment and the effects of foam quality on the capabilities of the systems.

It is recommended that the system parameters (a minimum fill rate of 1 meter per minute and a maximum expansion ratio of 1000:1) defined in SOLAS/FSS Code be replaced by an approval test (a modified version of MSC/Circ. 848 is recommended for this application).

Based on our testing, the parameters of MSC/Circ. 848 appear to provide sufficient challenge and range to adequately test systems against conditions likely in machinery space fires. The difficulty observed in extinguishing spray fires and, conversely, the ease in extinguishing the pan fires, demonstrates that the current high expansion foam test protocol (MSC/Circ. 670) is inadequate for approving HEFFSS for machinery space applications. As a result, it is recommended that a modified version of MSC/Circ. 848 serve as the basis for approving HEFFSS for machinery space applications.

The new protocol will need to account for the differences between high expansion foam and gaseous agent technologies (namely, discharge times). These differences need to be reflected in both the fill rate and extinguishment time requirements of the system. A maximum fill time of two minutes and an extinguishment time of five minutes or less is recommended for this application/technology. The protocol will need additional instrumentation to ensure accurate determination of extinguishment of fires due to the displacement of flames by the foam. Additional modifications may also be required once the mechanisms of extinguishment and foam quality issues are better understood.

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1.0 INTRODUCTION

The United States Coast Guard (USCG) is currently considering the use of High Expansion Foam Fire Suppression Systems (HEFFSS) for protecting shipboard machinery spaces, an application where there is only limited performance data. Although the USCG has never been solicited for a "type approval" for these systems, there are systems that have received approvals from other Administrations for use in shipboard machinery spaces per the requirements in the document Safety of Life at Sea (SOLAS) [International Maritime Organization, 2001a] and based on testing conducted against the two test protocols described in the International Code for Fire Safety Systems (FSS Code) [International Maritime Organization 2001b]. (MSC circular 670, "Guidelines for the Performance and Testing Criteria and Surveys of High Expansion Form Concentrates for Fixed Fire-Extinguishing Systems," and MSC circular 582, "Guidelines for the Performance and Testing Criteria, and Surveys of Low-Expansion Foam Concentrates for Fixed Fire-Extinguishing Systems.")

To assist the USCG in developing a position on the use of HEFFSS in machinery space applications, a series of full-scale fire tests were conducted to define the capabilities and limitations of these systems in this application. The results of this evaluation are presented in this report.

2.0 OBJECTIVES

The objectives of this test program were to define the capabilities and limitations of HEFFSS in shipboard machinery space applications and to assess the adequacy of these systems for this application.

3.0 TECHNICAL CONSIDERATIONS

HEFFSS hardware and fire scenario in MSC/Circ. 670 are not considered representative of the conditions and hazards of a shipboard machinery space MSC/Circ. 670 consists of a 1.73 m^2 heptane pan fire conducted in a 2 m x 2 m x 1 m enclosure. The enclosure is made of wire mesh. A specific size (6.1 Lpm at 500 kPa) high expansion foam generator is used to extinguish the fire during the test. There does not appear to be any correlation between the foam generator used

during the test and those installed on the ship (the ones installed on the ship should have a significantly greater capacity). In order to successfully complete the test, the fire must be extinguished within 120 seconds of system activation.

Since MSC/Circ. 670 is not considered representative of machinery space applications and hazards, the first step was to identify a set of tests in which to evaluate these suppression systems. There are currently three International Maritime Organization (IMO) test protocols for approving other technologies for machinery space applications. These include the standard for approving water-based (mist) systems (MSC circular 668/728), the gaseous agent test protocol (MSC circular 848), and the fixed aerosol test protocol (MSC circular 1007). All three protocols are conducted in a full-scale 500 m^3 machinery space containing a simulated diesel engine mockup. A significant effort went into developing these protocols to make them representative of typical machinery space conditions and hazards.

After a review of the three MSC circulars, the gaseous agent test protocol (MSC circular 848) was selected to be the basis of this investigation. During the review, the water mist standard (MSC circular 668/728) was eliminated due to the large number of required tests and the test configuration which includes a large vent opening that would allow the foam to flow out of the compartment. The aerosol standard is similar to the gaseous agent standard and was eliminated due to the small size of the test fires. It was believed that the larger fires would present a greater challenge to the HEFFSS.

The gaseous agent test protocol consists of four tests. The first test is an agent distribution test conducted against small cup fires located in the corners of the compartment and was not included in this evaluation. The remaining three tests consist of combinations of spray, pan, and wood crib fires allowing an assessment of the HEFFSS capabilities against a range of fires sizes, types, and locations (elevations and degree of obstruction).

4.0 TEST COMPARTMENT

The tests were conducted in a simulated machinery space aboard the test vessel, STATE OF MAINE, at the U.S. Coast Guard Fire and Safety Test Detachment located at Little Sand Island in Mobile, AL. The machinery space was located on the fourth deck of the Number 6

cargo hold. The compartment was constructed to meet the dimensional requirements of the IMO test protocol (MSC/Circ. 848). The compartment volume was approximately 500 m^3 with nominal dimensions of 10 m x 10 m x 5 m as shown in figure 1. The diesel engine mockup described in the test protocol was located on the fourth deck in the center of the compartment as shown in figure 2. Air to support combustion was provided naturally through two 2 m^2 vent openings located on the fourth deck forward in the compartment. These two vents were equipped with remotely activated retractable doors. Products of combustion were exhausted from the compartment through a 6 m^2 vertical stack located in the back of the compartment (aft). The exhaust stack was equipped with a remotely activated hydraulic damper. The supply vents (the four doors and the two IMO vents) were open during the preburn period and closed just prior to agent discharge. The vertical stack remained open for the entire test.

5.0 FIRE SCENARIOS

The fire scenarios required by MSC circular 848 are listed in table 1 and are designated using the following numbers: 1, 2A, 2B, 3, and 4. The locations of these fires are shown in figure 3. Halocarbon agents are evaluated against fire Scenarios 1, 2A, 3, and 4, with the inert gases tested against fire Scenarios 1, 2B, 3, and 4.

The halocarbon fire tests (1, 2A, 3 and 4) were selected as the basis for this evaluation since they have a higher heat release rate than the fires required for the inert gases.

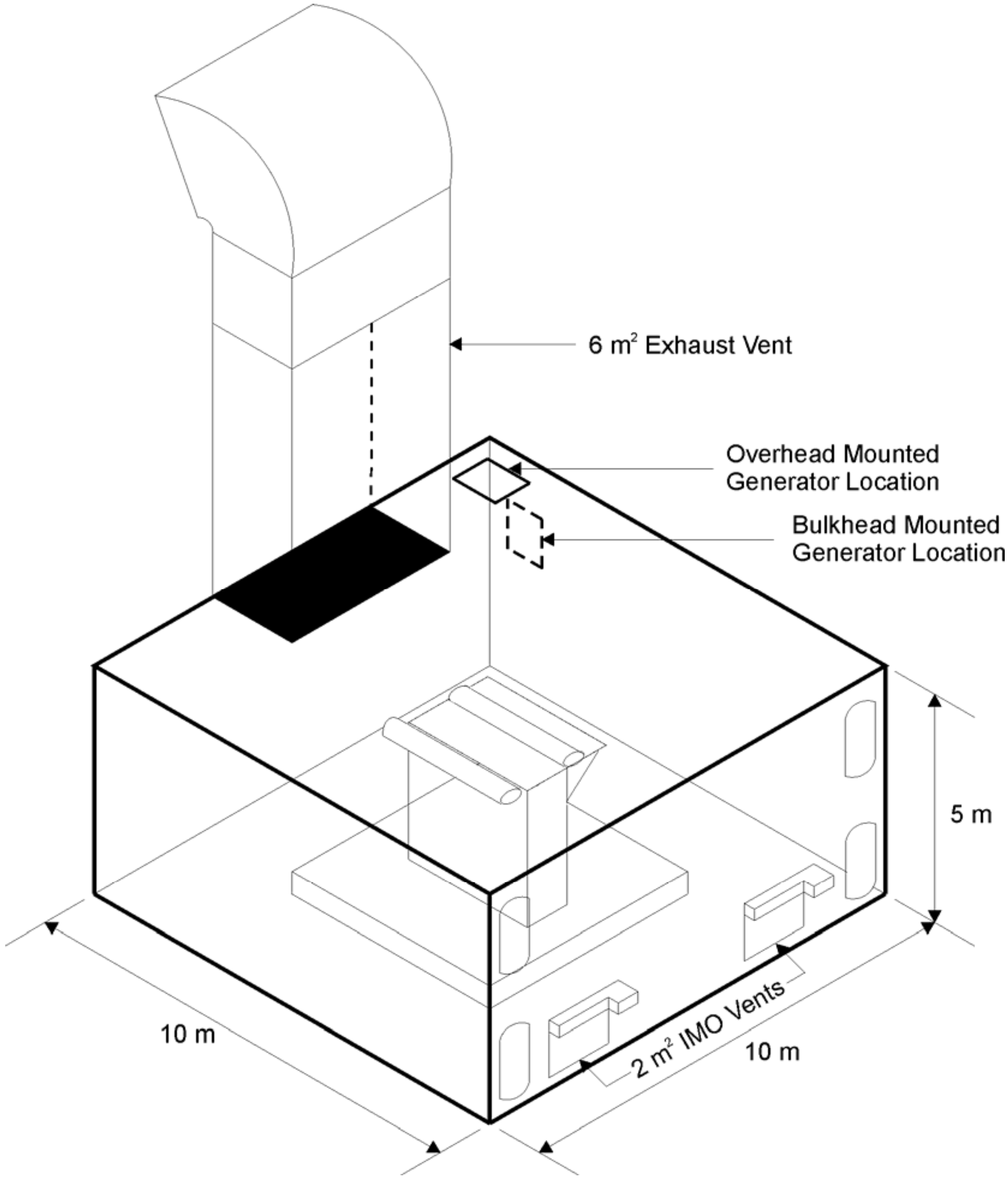
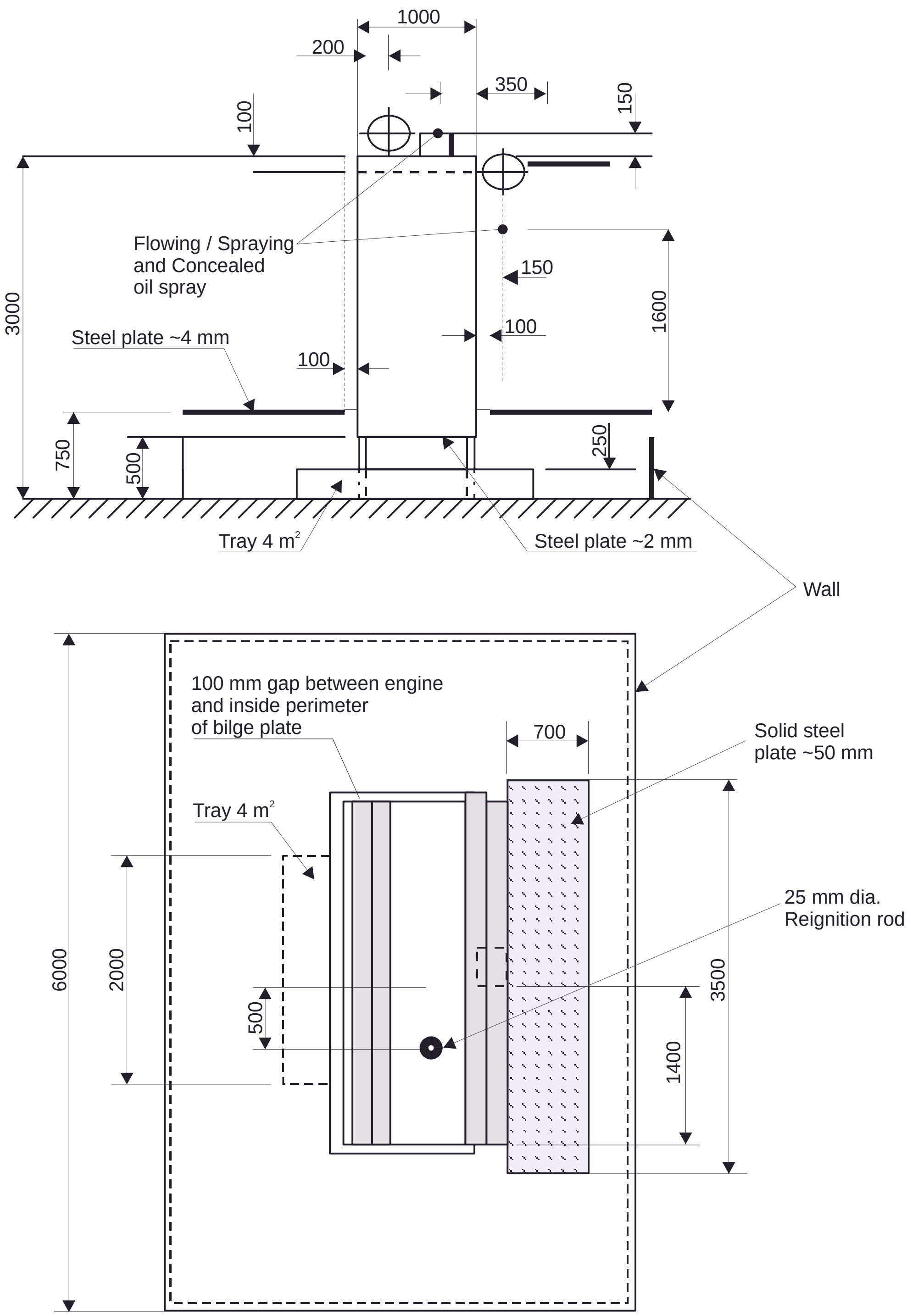
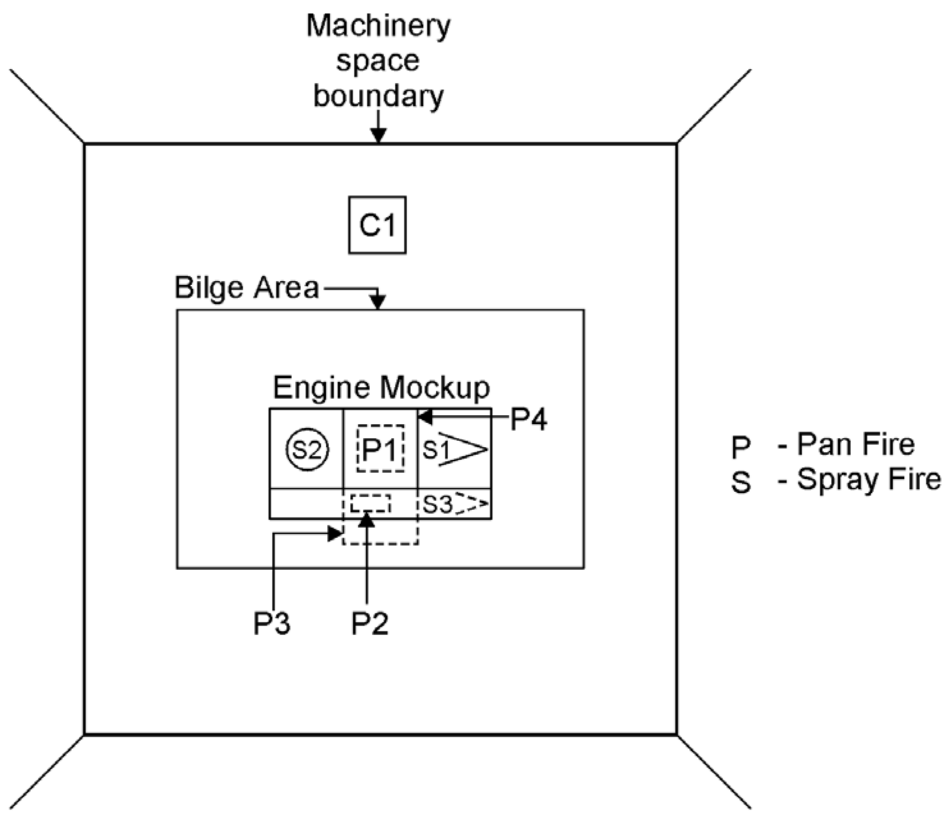


Figure 1. Machinery Space Configuration.



(All measurements are in mm, unless otherwise noted.)

Figure 2. Diesel Engine Mockup (Section and Plan Views).



Plan View

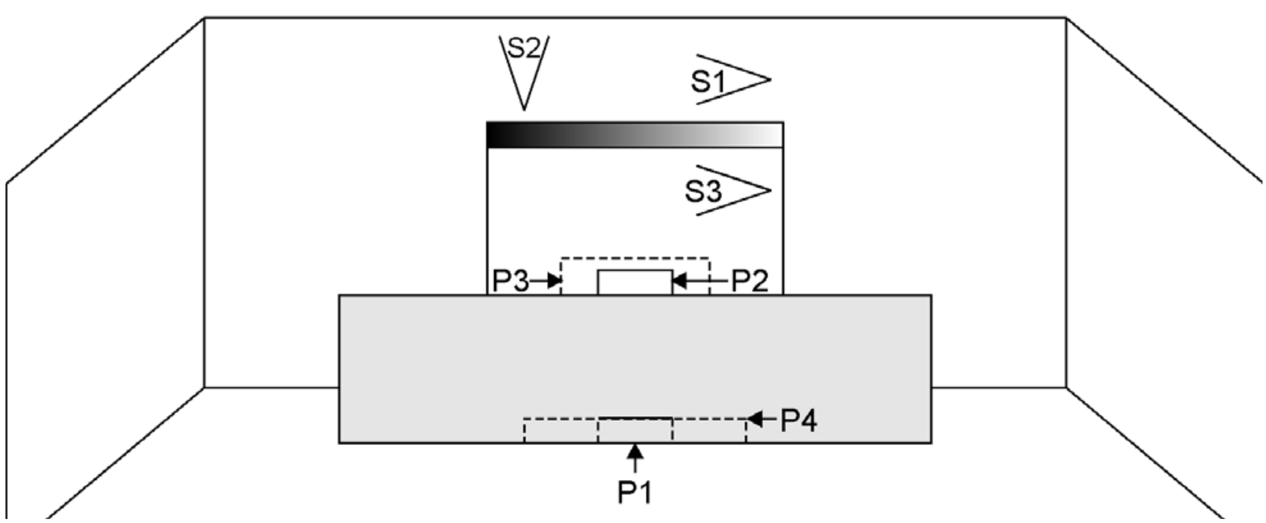


Figure 3. Fire Locations.

The telltale fire scenario (Scenario 1) was eliminated since it does not apply to this technology. The telltale fire test is intended to define three critical parameters of gaseous agent systems: minimum extinguishment concentration, minimum nozzle pressure and the mixing characteristics of the system. None of these parameters are associated with this technology. As a result, the fire scenarios that served as the basis of this evaluation are shown as the shaded areas on table 1.

Table 1. Fire Scenarios.

Fire Scenario	Nominal Total Heat Release Rate	Components	Nominal Heat Release Rates	Location (Figure 3)
1	~24 kW	82 cm^2 heptane pan fires (telltales)	~3 kW/ea	Corners (TT)
2A	7.95 MW	Low pressure heptane spray fire High pressure diesel spray fire 0.25 m^2 heptane pan fire	5.8 MW 1.8 MW 0.35 MW	Top of mockup (S1) Top of mockup (S2) Under mockup (P1)
2B	0.49 MW	0.10 m^2 heptane pan fire 0.25 m^2 heptane pan fire	0.14 MW 0.35 MW	Side of mockup (P2) Under mockup (P1)
3	4.40 MW	Low flow heptane spray fire Wood crib 2.0 m^2 diesel pan fire	1.10 MW 0.30 MW 3.00 MW	Side of mockup (S3) Deck level (C1) Bilge Plate (P3)
4	6.00 MW	4.0 m^2 diesel pan fire	6.00 MW	Bilge (P4)

Additional fire tests were also conducted to further identify the capabilities and limitations of each system. Evaluations were conducted to determine how specific HEFFSS design parameters and test conditions (e.g., fire scenarios) affect the fire extinguishing capabilities of these systems. This evaluation included an assessment of compartment fill rate, extinguishment difficulty as a function of fire parameters (e.g., fire type, size, fuel and location) and how the use of inside air (products of combustion) affects the capabilities of the system. To reduce the time/cost of testing, each system was assessed against a different parameter/parametric assessment. These parametric assessments were conducted using the most challenging fires listed in table 1.

The fuel pans used during these tests were square in shape and constructed of 3.2 mm steel plate with welded joints. The pans were 22.9 cm in depth with side dimensions of 31.6 cm, 50 cm, 144 cm, and 200 cm for the 0.2 m^2, 0.25 m^2, 2 m^2, and 4 m^2 pans, respectively. These pans were filled with a 2.5 cm deep layer of water and a 5 cm deep layer of either heptane or diesel fuel. Heptane was added to the 2 m^2 and 4 m^2 diesel pans to initiate the fire (1.9 L and 3.8 L respectively).

The wood crib used in Fire Scenario 3 consisted of 4 layers of 6 members each. Each member was trade size 5 × 5 × 45 cm (actual 3.8 × 3.8 × 45 cm) fir lumber with a moisture content between 9 percent and 13 percent. The wood crib was placed on an angle iron frame 0.3 m above the deck. The crib was ignited using a 0.25 m^2 pan that was fueled with 3.8 L of heptane.

The spray fire parameters are given in table 2. The low-pressure heptane spray fires were produced using a pressurized fuel tank and a pipe network constructed of 1.2 cm diameter stainless steel tubing. The fuel tank was pressurized with nitrogen from a regulated cylinder. The high-pressure diesel spray was produced using a positive displacement pump and a pipe network constructed of 1.2 cm stainless steel tubing. Both systems were remotely actuated using solenoid valves and were equipped with a quarter turn ball valve for safety reasons.

Table 2. Spray Fire Parameters.

Fire Type	Low Pressure Heptane	Low Pressure, Low Flow Heptane	High Pressure Diesel
Spray nozzle	Wide spray angle (120°-125°) full cone type	Wide spray angle (80°) full cone type	Standard angle (at 6 bar) full cone type
Nozzle make and model	Bete Fog Nozzle P-120	Bete Fog Nozzle P-48	Spraying Systems LN-8
Fuel flow	0.16 ± 0.01 kg/s	0.03 ± 0.005 kg/s	0.050 ± 0.002 kg/s
Fuel temperature	20 ± 5 °C	20 ± 5 °C	20 ± 5 °C
Nominal heat release rate	5.8 ± 0.6 MW	1.1 ± 0.1 MW	1.8 ± 0.2 MW

The fires were ignited to achieve the MSC/Circ. 848 preburn times, prior to foam discharge, of 360 seconds for wood cribs, 120 seconds for pan fires, and 15 seconds for spray fires.

In order for a gaseous agent system to successfully complete MSC/Circ. 848, all Class B fires must be extinguished within 30 seconds of the end of agent discharge and the mass loss of the wood crib in Fire Scenario 3 cannot exceed 60 percent of its original weight. This implies that the wood crib must be extinguished during the tests.

6.0 EXTINGUISHING SYSTEMS

The three HEFFSS/manufacturers in this evaluation were Ansul Inc., Buckeye Fire Equipment, and Chemguard Inc. Each manufacturer was responsible for the design of their respective system. These designs were based on the minimum SOLAS/FSS Code requirements plus some additional capacity to provide a factor of safety for these tests.

Each system contained two basic parts: a foam concentrate proportioning system and water motor driven foam generator(s). The Ansul and Chemguard systems consisted of two generators, while the Buckeye system consisted of only one. The generator(s) were installed either in the overhead of the space or high at the aft end of the port bulkhead. These locations were shown in figure 1. The HEFFSS designs are described in subsequent sections of this report and are summarized in table 3.

6.1 Ansul HEFFSS

The Ansul HEFFSS consisted of two 106 m^3/min foam generators (Model Number Jet-X-2A) installed high at the aft end of the port bulkhead and in the overhead of the space. Each generator was designed to discharge a 2.75 percent solution of Jet-X foam concentrate with an expansion ratio of about 545:1. The foam concentrate was proportioned using a proportioner (Model Number 71894) connected to an Ansul 190 l bladder tank (Part Number 70501/70502).

Table 3. HEFFSS Design Summaries (Manufacturers' Data).

		Manufacturer	Manufacturer	Manufacturer
Foam Concentrate	Name	Ansul	Buckeye	Chemguard
	Potential Expansion Ratios	50:1 to 1000:1	up to 1000:1	up to 1000:1
	Proportioning Concentration	2.75%	2.2%	2%
	Flow Rate (Lpm)	6.9/13.8	10.4	4.8/9.6
Foam Generator	Model Name / Number	Jet-X-2A	BF-HIEX-50	3000WP
	Part Number	420001	FG-5000	M456345
	Vol. Flow Rate (m^3/min)	106/212	236	113/226
	Expansion Ratio	545:1	500:1	475:1
	Foam Solution Flow Rate (Lpm)	250/500	473	240/480
	Solution Pressure (kPa)	700	600	560
	Power Source	Water	Water	Water
	Mounting Orientation	Bulkhead & Overhead	Overhead	Bulkhead & Overhead
Proportioning Device	Model / Part Number	71894	71894*	EF10322
	Type	Proportioner	Proportioner	Proportioner
	Size (in.)	2	2	1.5
Tank	Type	Bladder	Bladder	Bladder
	Model / Part Number	70501/70502	70501/70502	70501/70502
	Orientation	Vertical	Vertical	Vertical
	Capacity (L)	190	190	190
Supply Air Source		Outside	Outside	Inside & Outside

* Used Ansul proportioner during testing

The proportioning system was located outside the space on the 2nd Deck. Each generator was designed to discharge 250 Lpm of foam solution (water and foam concentrate) at a pressure of 700 kPa, which corresponded to a concentrate flow rate of 6.9 Lpm. A number of tests were also run in which the operating pressure of the generators was lowered to 300 kPa. A schematic of the system is shown in figure 4.

6.2 Buckeye HEFFSS

The Buckeye HEFFSS consisted of a single 142 m^3/min foam generator (Model Number: BF-Hiex-50) located in the overhead of the space. The generator was designed to discharge a 2.2 percent solution of Buckeye Hi-Ex concentrate with an expansion ratio of about 500:1. The concentrate was proportioned using the Ansul proportioning set-up from the previous tests. The system was designed to discharge 473 Lpm at a pressure of 600 kPa, which corresponded to a concentrate flow rate of 10.4 Lpm. A schematic of the system is shown in figure 4.

6.3 Chemguard HEFFSS

The Chemguard HEFFSS consisted of two 113 m^3/min foam generators (Model Number 3000 WP) installed high at the aft end of the port bulkhead and in the overhead of the space. Each generator was designed to discharge a 2 percent solution of Chemguard C2S Foam concentrate with an expansion ratio of about 475:1. The concentrate was proportioned using a Chemguard proportioner (Model Number EF10322). The system was designed to discharge 240 Lpm at a pressure of 560 kPa, which corresponds to a concentrate flow rate of 4.8 Lpm. A schematic of the system is shown in figure 4.

7.0 FOAM KNOCKDOWN SYSTEM

In order to expedite foam removal after each test, a foam knockdown system was installed in the overhead of the space. The knockdown system consisted of a three by three grid of Bete TF29-180-16 nozzles installed in the overhead of the space with a nominal 3.0 m nozzle spacing as shown in figure 5. The system was designed to discharge 340 Lpm of solution at an operating pressure of 280 kPa. The solution contained 90 percent water (Mobile bay water) and

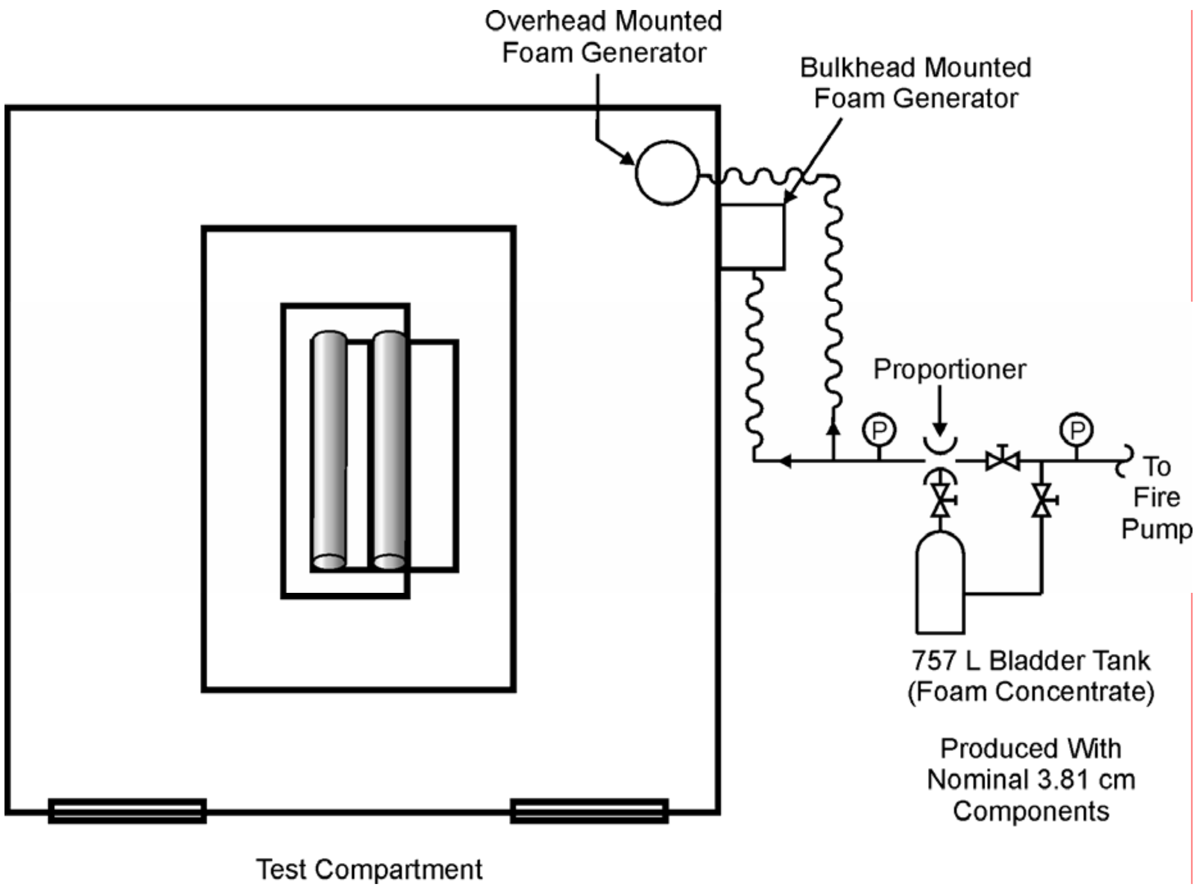


Figure 4. HEFFSS Schematic.

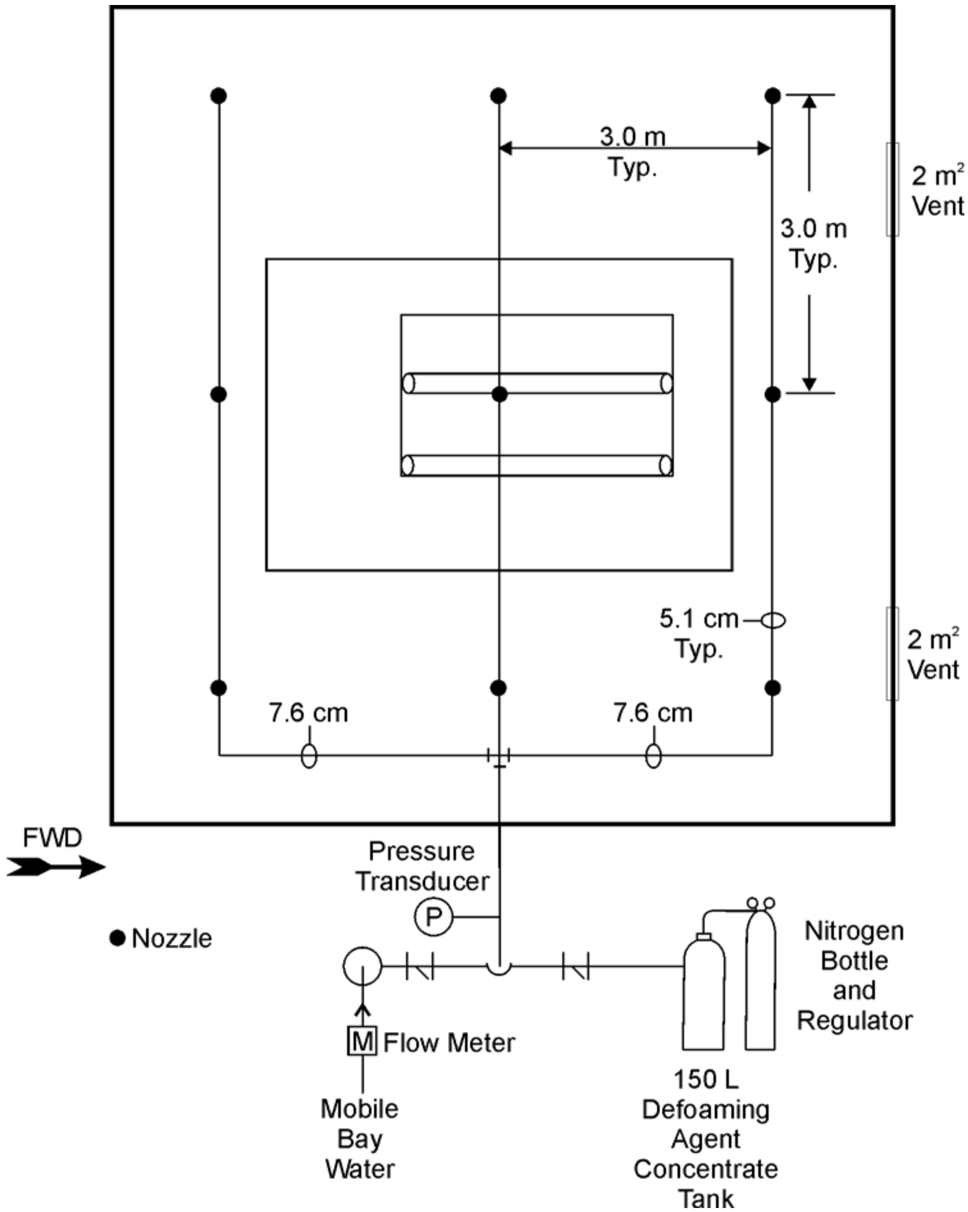


Figure 5. Foam Knockdown System.

10 percent defoaming agent (D-Foaming ST manufactured be SELIG Industries). The defoaming agent was injected into the water stream using the proportioning system also shown in figure 5.

Prior to testing, there were some concerns regarding the effect that residual defoaming agent may have on the development and buildup of foam in subsequent tests. This was shown not to be the case during a series of cold discharge tests conducted prior to using the defoaming agent. During the initial week, the foam was knocked down using only water from the overhead system. During the second and third weeks of testing, the foam was more robust requiring the use of the defoaming agent.

8.0 INSTRUMENTATION

Both the test compartment and the HEFFSS were instrumented for these tests. The instruments installed in the test compartment monitored both the thermal conditions in the space and the status of each fire during the test. The HEFFSS instrumentation was used to monitor the discharge characteristics of the system (flow rate and pressure). The U.S. Coast Guard's data acquisition system was used to collect all data at a rate of 1 scan per second. The instrumentation scheme is shown in figure 6.

8.1 Machinery Space and Fire Monitoring Instrumentation

The machinery space was instrumented to measure air temperatures; fire/flame temperature (to note extinguishment time); fuel system pressure; and O_2, CO_2, and CO gas concentrations. A more detailed description of these instruments is listed as follows.

8.1.1 Air/Gas Temperature Measurements

One thermocouple tree was installed in the center of the compartment. The tree consisted of nine thermocouples positioned at the following heights above the lower deck (0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, and 4.5 m). Inconel-sheathed, Type K thermocouples (0.32 cm diameter Omega Model KMQIN-125G-600) were used for this application.

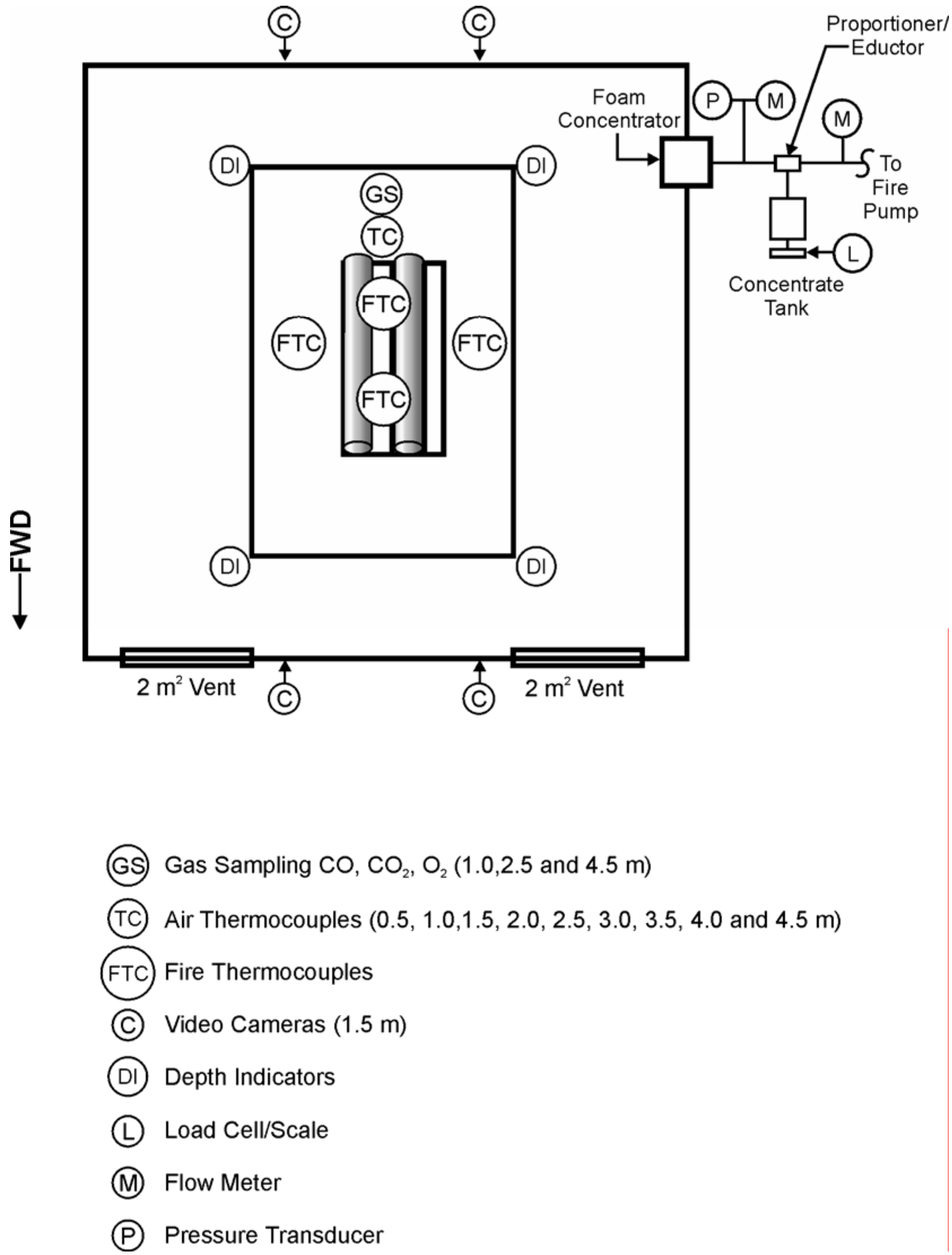


Figure 6. Compartment Instrumentation.

8.1.2 Fire Temperature Measurements

To aid in the determination of extinguishment time, each fire was instrumented for temperature. One thermocouple per fire was placed inside the wood crib in the flame region, 20 cm above the pan fires, and 45 cm downstream of the spray fire nozzles. Inconel-sheathed, Type K thermocouples (0.32 cm diameter Omega Model - KMQIN-125G-600) were used for this application. Additional thermocouples were added at the end of the first week of testing to further aid with the determination of extinguishment time.

8.1.3 Gas Concentration Measurements

Carbon monoxide, carbon dioxide, and oxygen concentrations were sampled in the center of the compartment at three elevations 1.0, 2.5 and 4.5 m above the deck as shown in figure 6. MSA Lira 3000 Analyzers with a full-scale range of 10 percent by volume were used to measure the carbon monoxide concentration. MSA Lira 303 Analyzers with a full-scale range of 25 percent by volume were used to monitor the carbon dioxide concentration. Rosemont 755 Analyzers were used to monitor the oxygen concentration with full-scale range of 25 percent by volume.

The gas samples were pulled through 0.95 cm stainless steel tubing and a Drierite packed filter using a vacuum sampling pump at a flowrate of 1 Lpm, resulting in a transport delay on the order of 10-20 seconds.

8.1.4 Fuel System Pressure Measurements

The fuel nozzle pressure for the spray fires was monitored approximately six meters upstream of the nozzles where the fuel line enters the test chamber. The two low-pressure spray fires were monitored using a Setra Model 205-2 pressure transducer with a full-scale range of 1.7 MPa. The high-pressure spray fire was monitored using a Setra Model 205-2 pressure transducer with a full-scale range of 20.7 MPa.

8.1.5 Depth Indicators

Foam depth indicators were installed in each quadrant of the space. These depth indicators were monitored manually during the cold agent discharge test(s). The depth indicators consisted of a pole running the height of the compartment with markings every 0.5 meters (0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5 m). During the initial test of each system (cold discharge test), the fill rate and expansion ratio of the system were determined by averaging the results of the four height measurements as a function of time.

8.2 HEFFSS Instrumentation

The HEFFSS was instrumented to measure the system operating pressure and flow rate during the test. Both the total solution and concentrate volumetric flow rates were measured. A more detailed description of these instruments is listed as follows.

8.2.1 HEFFSS Pressure Measurements

System pressures were measured at the inlets to the foam-proportioning device and the high expansion foam generator(s). Setra Model 205-2 pressure transducers were used for this application. These transducers have a range of 0-1750 kPa with an accuracy of 0.01 percent full-scale.

8.2.2 HEFFSS Flow Rate Measurements

For each system, the volumetric flow rate of the foam solution was measured at the inlet to the high expansion foam generator(s). This measurement was used in conjunction with the measured fill rate to calculate the volumetric expansion ratio of the foam solution. The total solution flow rate was measured using a Flow Technologies Inc. paddle wheel flow meter with a full-scale range of 0-1500 Lpm and an accuracy of 1.0 percent of the measured value.

The foam concentrate flow rate was measured using a Hoffer Inc. flow meter (Model H01/4-135) with a range full-scale of 0.95-13.2 Lpm and an accuracy of 1 percent of the measured value. For the Chemguard system, it was not possible to measure the concentrate flow rate using this device because the higher viscosity of the foam concentrate prevented the flow

meter from functioning correctly. As a result, the concentrate flow rate of the Chemguard system was determined based on the amount of concentrate consumed during each test and the duration of the discharge. In all cases, the solution concentration was estimated based on the solution and concentrate flow rate measurements.

8.3 Video Equipment

Five video cameras were used to visually document the events of the tests. Two video cameras were located inside the compartment adjacent to the fire locations (scenario specific locations). The other three cameras were located outside the compartment primarily viewing the area around the diesel engine mockup. A microphone was also installed in the center of the space to provide the audio for the five video cameras.

9.0 PROCEDURES

The tests were initiated from the control room located on the second deck level forward of the test compartment. Prior to the start of the test, the pans were fueled, and the compartment ventilation condition was set. The two 2 m^2 lower vents and the 6 m^2 stack vent were opened prior to the start of the test. The video and data acquisition systems were activated, marking the beginning of the test. One minute after the start of the data acquisition system, the fires were ignited, and the compartment was cleared of test personnel. The preburn times of the fires in the tests defined the ignition sequence timing. Wood crib fires were ignited 360 seconds prior to systems activation. Pan fires were ignited 120 seconds prior to systems activation. Spray fires were ignited 15 seconds prior to systems activation. Ten seconds prior to foam discharge, the two lower vents into the space were closed and HEFFSS was activated. The large stack damper remained open for the duration of the test to prevent the oxygen depletion in the compartment from extinguishing the test fires. [The fuel for the spray fires was secured shortly after the fire was thought to be extinguished due to a decrease in temperature measured by the fire thermocouples and the lack of visible flames.] The test continued for ten minutes after HEFFSS activation or until all of the fires had been extinguished. On completion of the test, the overhead foam knockdown system was activated to prepare the space for the next test. Once the foam was sufficiently reduced below the ventilation openings, the space was ventilated in preparation for the next test.

10.0 RESULTS AND DISCUSSION

10.1 General Results

A total of 35 tests were conducted during this evaluation. These 35 tests consisted of 14 tests using the Ansul system, 11 tests using the Buckeye system and 10 tests using the Chemguard system.

In addition to the four tests required by MSC circular 848, a parametric study was conducted with each system (different parameters were evaluated for each system). These parameters included fill rate, expansion ratio, and extinguishment difficulty as a function of fire type, size and location. The parameters also included how the use of inside (dirty air/vitiated gasses) affects the fire extinguishing capabilities of the system. The results of these tests are discussed in the following sections.

The data recorded during each test are provided in Appendix B. These measurements include the temperature and oxygen profiles/histories in the compartment, the thermocouples installed in the flames, and the discharge characteristics of the system (pressures and flow rates).

10.1.1 Problems Determining Extinguishment Times

At times, it was difficult to confirm that the fire was extinguished using either visual observations or instrumentation. This was especially true for the spray fires. As the foam engulfed the spray fire, there were times where no flames were visible in the compartment. The foam blanket was calm and there was no indication of any fire beneath. After a few seconds, a flame would burst from the foam blanket and continuously burn in the compartment. Over time, this flame/jet would be covered again by the foam, and the cycle would repeat. These conditions were only visible for the short period of time before the compartment was completely full of foam.

As a result of this difficulty in using visual observations to determine extinguishment, a greater emphasis was placed on using the thermocouples installed in the space to monitor the status of the fire. As will be discussed in the following paragraphs, using these temperatures to determine extinguishing time was also somewhat problematic.

Figure 7 is a plot of the temperatures measured by the thermocouples installed in and around the fire in Ansul Test #5. At two and a half minutes into the test, the fire appeared to be extinguished (no visible flames, no motion/bubbling of the foam blanket and all of the thermocouples where rapidly approaching ambient temperatures). Approximately three and a half minutes later, the fuel to the spray fire was secured. Immediately after the fuel was secured, the temperatures near the fuel nozzle dropped only 35 ºC. This indicated that there were still flames somewhere in the compartment when the fuel was secured. It is believed that the fire may move away from the fuel source and burn in void/air pockets in the foam. A short period of time later, flames were also observed in the compartment (orange flashes were observed on the video being recorded inside of the space).

To address possible displacement of the flames by the foam, additional thermocouples were placed around each fire between the first and second weeks of testing. Securing the fuel spray was also delayed for at least one minute after the fire appeared to be extinguished. Even with these additional precautions, there were still a limited number of tests where the fuel was secured prior to the fire being completely extinguished.

10.1.2 Extinguishment Difficulty

Consistent with the literature (Ingason, 1992), the pan fires were easily extinguished and spray fires presented a major challenge to the HEFFSS. Independent of the system tested (foam type, hardware, fill rate, etc.), when the foam reached the height of the pan fires, the foam quickly flowed across the fuel surface and the fire was extinguished. The spray fires on the other hand were much more difficult to extinguish. In some instances, the spray fires were never

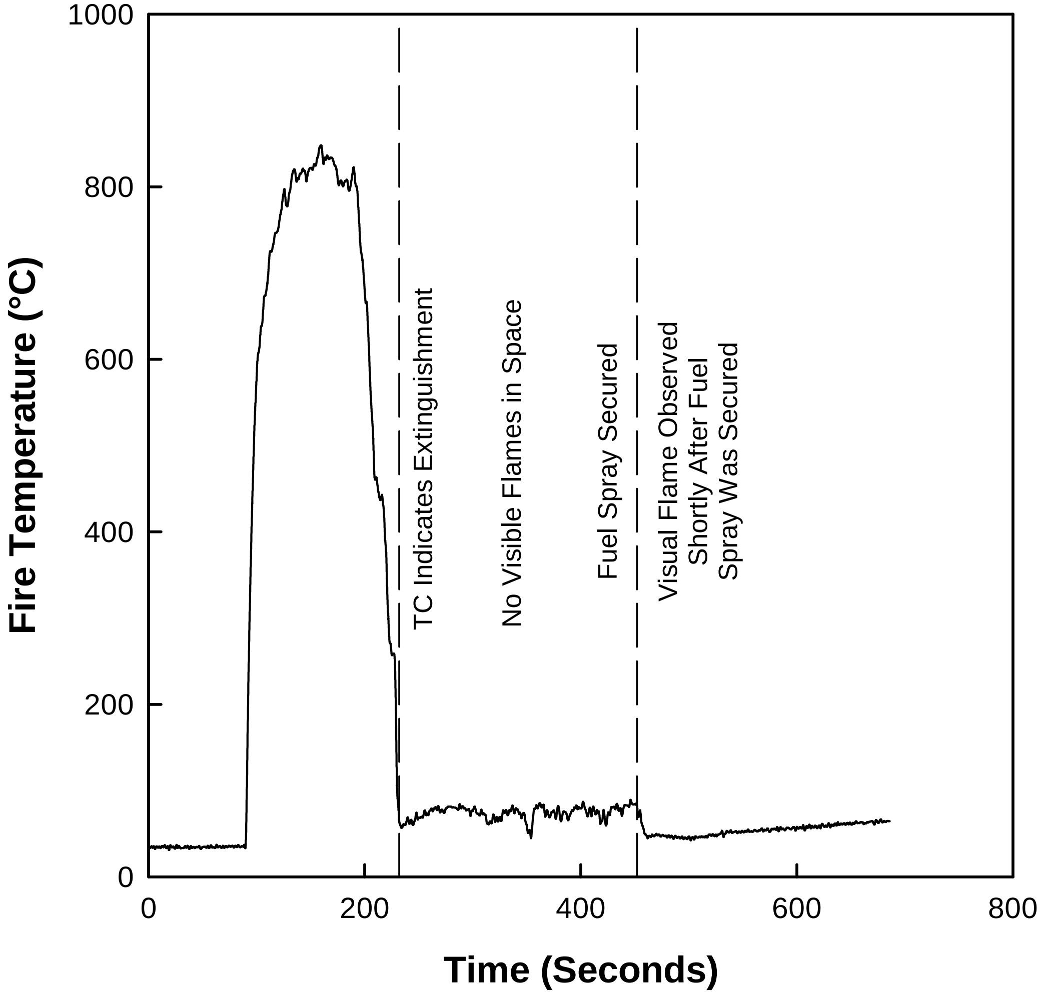


Figure 7. Typical Spray Fire Temperature History.

extinguished. The majority of the spray fires that were extinguished required foam depths of 2-5 meters above the height of the fire location. Many times, the spray fires were not extinguished until the machinery space was completely filled with foam and the foam was pushed out of the vents of the compartment. This raises the question to whether HEFFSS can adequately protect extremely large machinery spaces.

The difficulty extinguishing the spray fires was observed early into the first week of testing. To increase the likelihood of success for the remaining tests, it was decided to abandon the SOLAS/FSS fill rate of 1 m/min and use the maximum rate obtainable with the equipment at hand.

10.2 Specific Results

10.2.1 Ansul HEFFSS Results

Fourteen tests were conducted with the Ansul HEFFSS. The fourteen tests included two cold discharge tests, six tests conducted against the fire scenarios required by MSC circular 848 and six spray fire tests. The spray fire tests were added to the Ansul test series (not in the test plan) due to difficulties observed extinguishing these fires during the first couple of tests. The results of these tests are summarized in table 4.

To allow the flexibility of increasing the fill rate during the test series, Ansul provided two Jet-X-2A generators. During the first fire test, (Test 3 – Scenario 3), the single generator system failed to extinguish the 1.1 MW heptane spray fire on the side of the mockup. To increase the likelihood for success during the remaining tests, the higher fill rate/two generator system was used with the Ansul system.

For the two generator system, one of the generators was installed in the bulkhead and the other in the overhead of the space. The system was operated at approximately 700 kPa for a majority of the tests. During the fill rate parametric assessment, a limited number of tests were also conducted with an operating pressure of 350 kPa. At the higher operating pressure (700 kPa), the system produced foam with an expansion ratio of about 320:1 and a fill rate

Table 4. Ansul Test Results.

Test Number	Fire Scenario	Individual Fires	System Pressure	Fill Rate	Expansion Ratio	Extinguishment Time
			[kPa]	[m/min]		[sec]
1*	Cold Discharge		650	0.9	390:1	
2	Cold Discharge		675	1.6	320:1	
3*	Scenario 3	2 m^2 Diesel Pan	760	0.9	320:1	59
		Wood Crib				330
		1.1 MW Heptane Spray				No @ 350
4	Heptane Spray on Side	1.1 MW Heptane Spray	700	1.6	320:1	No @ 540
5	Heptane Spray on Side	1.1 MW Heptane Spray	670	1.6	320:1	No Ext
6	Scenario 3	2 m^2 Diesel Pan	700	1.6	320:1	20
		Wood Crib				200
		1.1 MW Heptane Spray				No Ext
7	Scenario 2A	.25 m^2 Heptane Pan	700	1.6	320:1	65
		1.8 MW Diesel Spray				No @ 330
		5.8 MW Heptane Spray				No @ 330
8	Scenario 2A	.25 m^2 Heptane Spray	670	1.6	320:1	55
		1.8 MW Diesel Pan				590
		5.8 MW Heptane Spray				590
9	Scenario 2A	.25 m^2 Heptane Pan	700	1.6	320:1	60
		1.8 MW Diesel Spray				No Ext
		5.8 MW Heptane Spray				No Ext
10	Scenario 4 -	4 m^2 Diesel Pan	700	1.6	320:1	60
11	2 Sprays - Deck Level	1.8 MW Diesel Spray	700	1.6	320:1	245
		5.8 MW Heptane Spray				245
12	2 Sprays - Deck Level	1.8 MW Diesel Spray	340	1.4	390:1	310
		5.8 MW Heptane Spray				310
13	Heptane Spray on Side	1.1 MW Heptane Spray	340	1.4	390:1	No Ext
14	Heptane Spray on Side	1.1 MW Heptane Spray	370	1.4	390:1	No Ext

* Tests conducted with a single foam generator

No Ext = No extinguishment

of 1.6 m/min. The lower pressure resulted in a reduced fill rate (1.4 versus 1.6) but the expansion ratios remained relatively the same.

The Ansul HEFFSS was evaluated during the first week of full-scale testing. As stated in Section 10.1.1, it was difficult to determine when the spray fires had been extinguished. As a result, some of the tests conducted with the Ansul system were stopped prematurely (the fuel was secured prior to the fire being extinguished and/or before the end of the ten minute of discharge period). These tests are indicated in table 4.

To summarize the results, the two-generator Ansul system quickly extinguished the pan fires (Tests 3, 6, and 10) but could not consistently extinguish the spray fires. The system was capable of extinguishing spray fires located low in the space (Tests 11 and 12) but only extinguished two (Test 8) of the twelve spray fires located above deck level (on the side or on the top of the mockup).

10.2.2 Buckeye HEFFSS Results

The Buckeye HEFFSS consists of a single generator installed in the overhead of the space. The system was operated at approximately 600 kPa producing foam with an expansion ratio of about 300:l and a fill rate of 1.7 m/min.

Eleven tests were conducted with the Buckeye HEFFSS. These tests include two cold discharge tests, the three tests required by MSC circular 848, and six tests conducted against spray fires (parametric assessment). The results of the tests are summarized in table 5.

The Buckeye HEFFSS was capable of extinguishing all of the fires conducted during this evaluation. Consistent with the previous tests, the spray fires presented the greatest challenge requiring in some cases over seven minutes to extinguish (Tests 4 and 11). The results of the spray fire parametric study will be discussed later in this report.

Table 5. Buckeye Test Results.

Test Number	Fire Scenario	Individual Fires	System Pressure	Fill Rate	Expansion Ratio	Extinguishment Time
			[kPa]	[m/min]		[sec]
1	Cold Discharge		425	1.3	330:1	
2	Cold Discharge		600	1.7	290:1	
3	Scenario 4	4 m^2 Diesel Pan	600	1.7	290:1	55
4	Scenario 3	2 m^2 Diesel Pan	600	1.7	290:1	15
		Wood Crib				30
		1.1 MW Heptane Spray				430
5	Vertical Diesel Spray - Deck Level	1.8 MW Diesel Spray	600	1.7	290:1	42
6	Horizontal Heptane Spray - Deck Level	5.8 MW Heptane Spray	600	1.7	290:1	370
7	Horizontal Heptane Spray - Deck Level	2 MW Heptane Spray	580	1.7	290:1	87
8	Vertical Diesel Spray - Top of Mockup	1.8 MW Diesel Spray	590	1.7	290:1	140
9	Horizontal Heptane Spray - Top of Mockup	2 MW Heptane Spray	590	1.7	290:1	330
10	Horizontal Heptane Spray - Top of Mockup	5.8 MW Heptane Spray	585	1.7	290:1	370
11	Scenario 2A	.25 m^2 Heptane Pan	590	1.7	290:1	66
		1.8 MW Diesel Spray				430
		5.8 MW Heptane Spray				430

10.2.3 Chemguard HEFFSS Results

The Chemguard HEFFSS consisted of two (2) model 3000 WP foam generators. When tested with inside air, the two generators were installed side-by-side high in the space. When tested with outside air, one generator was installed in the bulkhead and the other one in the overhead of the space. The system was operated at approximately 400 kPa. When clean outside air was used to make the foam, the foam expansion ratio was approximately 250:1 resulting in a fill rate of 1.5 m/min. These parameters were dramatically reduced when the products of combustion were used to make the foam (250:1 versus 30:1).

Ten tests were conducted with the Chemguard HEFFSS. Five tests were conducted with inside air (Tests 1-5) and five tests were conducted with outside air (Tests 6-10). The results of the tests are summarized in table 6.

Table 6. Chemguard Test Results.

Test Number	Fire Scenario	Individual Fires	System Pressure	Source of Air	Fill Rate	Expansion Ratio	Total Foam Flow Time	Extinguishment Time
			[kPa]		[m/min]		[sec]	[sec]
1	Scenario 4	4 m^2 Diesel Pan	400	Inside	0.15	30:1	370	160
2	Cold Discharge		350	Inside	1.5	250:1	30	
3	Scenario 4	4 m^2 Diesel Pan	400	Inside	0.15	30:1	250	65
4	Scenario 3	2 m^2 Diesel Pan	400	Inside	0.15	30:1	640	405
		Wood Crib						130
		1.1 MW Heptane Spray						630
5	Horizontal Heptane Spray - Deck Level	5.8 MW Heptane Spray	350	Inside	0.15	30:1	410	No Ext
6	Cold Discharge		310	Outside	1.5	250:1	35	
7	Scenario 3	2 m^2 Diesel Pan	400	Outside	1.5	250:1	205	95
		Wood Crib						65
		1.1 MW Heptane Spray						195
8	Scenario 4	4 m^2 Diesel Pan	400	Outside	1.5	250:1	75	35
9	Horizontal Heptane Spray - Deck Level	5.8 MW Heptane Spray	390	Outside	1.5	250:1	320	205
10	Scenario 2A	.25 m^2 Heptane Pan	375	Outside	1.5	250:1	270	30
		1.8 MW Heptane Spray						245
		5.8 MW Diesel Spray						245

The initial tests conducted with the system were run using inside air. During these tests, the hot and smokey gases were observed to significantly impact the system's ability to make foam. During the tests conducted with diesel fuel (namely Scenario 4), the foam produced by the system was very wet (low expansion ratio) and was observed to have the consistency of foam shaving cream (i.e., somewhat stiff). During the tests conducted with the larger fires that produced higher gas temperatures in the upper layer, the foam was very light and dry. In either case, both the fill rate and expansion ratio of the foam were significantly reduced by the use of inside air.

HEFFSS that use inside air are only capable of filling the compartment with foam to the height of the generator. As a result, MSC/Circ. 848 Scenario 2A was modified for the test conducted using the Chemguard HEFFSS with inside air. The modification consisted of moving the two large spray fires on top of the mockup (located above the generator) to deck level.

During the tests conducted with inside air, the Chemguard HEFFSS was capable of extinguishing two of the three fire scenarios required by MSC/Circ. 848 (Scenario 3 and 4). The Chemguard HEFFSS using inside air could not extinguish the large spray fire combination in Scenario 2A. The extinguishment times for the system using inside air were significantly longer than those observed for the system using outside air. The Chemguard HEFFSS using outside air was capable of extinguishing all of the test fires in about four minutes or less.

10.2.4 Results Summary

A total of 35 tests were conducted in this evaluation utilizing the equipment and concentrates from three manufacturers: Ansul, Buckeye and Chemguard. All of the systems produced foams with observed expansion ratios on the order of 300:1. This is much lower than published/advertised values (300:1 versus 500:1) of the manufacturers. The difference may be associated with how the expansion ratio is determined. During these tests, the expansion ratio was determined based on filling a compartment. The manufacturers' data may be based on the foam as it exits the generator (unknown). Also, the use of brackish water (Mobile Bay water) during these tests may have also contributed to the lower expansion ratio. The average system fill rate during these tests was on the order of 1.6 m/min.

All three systems easily extinguished the pan fires included in this evaluation independent of the fuel type (heptane or diesel). The differences in system capabilities were observed during the extinguishment of the spray fires (namely, the heptane spray fires). The heptane spray fires presented a major challenge to the HEFFSS. During the tests conducted with the heptane spray fires, the extinguishment times were in many cases, two to three times longer than it took to fill the compartment with foam during the cold discharge tests. Although the heptane spray fire was consuming some of the foam, a significant amount was observed flowing out of all of the openings in the compartment by the end of the test. Under certain conditions

(spray fire size, location/elevation and agent/system), there appears to be the need to compress the foam (making it denser and/or wetter at the fire location) in order to extinguish the heptane spray fires.

There were variations in the fire suppression capabilities (and foam quality) between the three manufacturers. The Buckeye and Chemguard systems produced more robust foam (i.e., hard to break down) and were both capable of extinguishing the heptane spray fires. The foam produced by these two systems was so robust, the space needed to be cleaned using a defoaming agent after each test. The Ansul foam was more fragile and had difficulty extinguishing the heptane spray fires. During cleanup, the Ansul foam was quickly broken down/washed away using short bursts of water. It is unknown whether the difficulty extinguishing the heptane spray fires was associated with the foam concentrate, foam generating equipment or both.

The results of these tests demonstrate the potential for using HEFFSS for protecting shipboard machinery spaces. However, most of the high expansion foam systems were developed and tested many years ago. Due to the niche market (namely aircraft hangars) there is only limited data defining the capabilities of these systems. In fact, when conducting the literature search, there was only one report (Ingason, 1992) that was applicable to this application. With the potential to become a Halon/CO_2 alternative in the maritime industry, the current manufacturers may be interested in pursuing additional development/optimization of there respective systems/technologies.

10.3 Parametrics Evaluation

An evaluation was conducted to determine how specific HEFFSS design parameters and test conditions (e.g., fire scenarios) affect the fire extinguishing capabilities of these systems. This evaluation included an assessment of compartment fill rate, extinguishment difficulty as a function of fire parameters (e.g., fire type, size, fuel and location) and how the use of inside air (products of combustions) affects the capabilities of the system.

10.3.1 Fill Rate

Increasing the fill rate has two effects on the fire extinguishing capabilities of the system. First, the foam reaches the fire and starts the extinguishment process sooner and second, the foam surrounds and advances toward the fire faster. This is important when considering that the radiation from the fire tends to breakdown the foam as it approaches. As a result, the higher fill rates tend to overwhelm the breakdown due to radiation, translating into faster extinguishment times and increased capabilities against larger fires. This is demonstrated in the comparisons shown in table 7.

As shown in table 7, higher fill rates translate into faster extinguishment times and the need for less foam to extinguish the fire (the amount of foam discharged into the space at the time the fires were extinguished was less for the higher fill rate systems). Based on these results, the minimum fill rate of 1 m/min stated in SOLAS/FSS Code should be significantly increased. This will be discussed in detail in section 10.4 of this report.

10.3.2 Fire Parameters

The fire parameters include fire type (spray or pan fire), fuel type, fire size and fire location. These parameters will be discussed in the following sections of this report.

10.3.2.1 Fire Type

Consistent with the literature, the pan fires were easily extinguished and the spray fires presented a major challenge to the HEFFSS. Independent of the system tested (foam type, hardware, fill rate, etc.), when the foam reached the height of the pan fires, the foam quickly flowed across the fuel surface and the fire was extinguished. The spray fires on the other hand were much more challenging and, in some cases, never extinguished.

Table 7. Fill Rate Comparison.

Test	Fire Scenario	System Pressure [kPa]	Fill Rate [m/min]	Enclosure Fill Time [min]	Individual Fires	Extinguishment Time [sec]	Total Foam Required [m^3]
Single Generator Tests							
ANSUL 3	Scenario 3	760	0.9	5.6	2 m^2 Diesel Pan	59	89
					Wood Crib	164	247
					1.1 MW Heptane Spray	No Ext	
ANSUL 6	Scenario 3	700	1.6	3.1	2 m^2 Diesel Pan	20	53
					Wood Crib	200	533
					1.1 MW Heptane Spray	No Ext	
Two Generator -Reduced Pressure Tests							
ANSUL 12	2 Sprays - Deck Level	340	1.4	3.6	1.8 MW Diesel Spray	310	710
					5.8 MW Heptane Spray	310	710
Two Generator -Full Pressure Tests							
ANSUL 11	2 Sprays - Deck Level	700	1.6	3.1	1.8 MW Diesel Spray	245	653
					5.8 MW Heptane Spray	245	653

It should be noted that going into these tests, even the manufacturers were uncertain of the capabilities of these systems against spray fires. The extinguishment of the spray fires typically occurred when foam depth was 2-5 meters above the height of the fire. Many times the spray fires were not extinguished until the machinery space was completely filled with foam and foam began to be pushed out of the openings of the compartment.

10.3.2.2 Fuel Type

There was no difference in the extinguishment difficulty of the diesel and heptane pan fires. However, the heptane spray fires were more difficult to extinguish than those produced with diesel fuel. This is assumed to be a function of the flashpoint of the fuel (heptane –4 °C, diesel >54 °C).

As shown in table 8, the diesel spray fires (Tests 5 and 8) were extinguished much faster than the heptane spray fires (Tests 7 and 9). During the diesel spray fire tests, the fire was quickly extinguished shortly after the foam reached the base of the fire. The heptane spray fires on the other hand would continue burning even after they were completely submerged beneath the foam blanket. As a result, the extinguishment times for the heptane spray fires were approximately two times longer than the diesel spray fires.

An uninvestigated variable that may have contributed to this behavior is the operating pressure of the fuel spray system. The high pressure diesel spray (10.4 Mpa) caused the actual combustion of the fuel to occur well above the nozzle, reducing the radiant exposure near the nozzle location. The lower pressure heptane spray fire (584 kPa) had the flames closer to the nozzle producing higher radiant exposures (and foam breakdown) near the nozzle.

Table 8. Fuel type (Diesel versus Heptane) Comparison.

Test	Fire Scenario	Fire Description	Extinguishment Time [sec]
Buckeye 5	Vertical Diesel Spray - Deck Level	1.8 MW Diesel	42
Buckeye 7	Horizontal Heptane Spray - Deck Level	2 MW Heptane	87
Buckeye 8	Vertical Diesel Spray - Top of Mockup	1.8 MW Diesel	140
Buckeye 9	Horizontal Heptane Spray - Top of Mockup	2 MW Heptane	330

10.3.2.3 Fire Size

During this evaluation, the larger spray fires resulted in longer extinguishment times. This is shown in table 9.

Table 9. Fire Size Comparison.

Test	Fire Scenario	Fire Description	Extinguishment Time [sec]
Buckeye 7	Horizontal Heptane Spray - Deck Level	2 MW Heptane Spray	87
Buckeye 6	Horizontal Heptane Spray - Deck Level	5.8 MW Heptane Spray	370
Buckeye 9	Horizontal Heptane Spray - Top of Mockup	2 MW Heptane Spray	330
Buckeye 10	Horizontal Heptane Spray - Top of Mockup	5.8 MW Heptane Spray	370

As stated previously, the larger fires break down the foam due to the heat build up in the compartment and increased radiant exposure around the base of the fire. Theoretically, there should be a critical fire size for each fill rate where the radiant breakdown of the foam is equal to the rate in which the form advances on the fire. This needs to be further investigated to fully understand the capabilities and limitations of these systems. Breakdown of foam due to hot metal surfaces (radiant exposures and contact with hot metal surfaces) should also be investigated.

10.3.2.4 Fire Location

A comparison of the extinguishing performance relative to the height of the fire above the deck is provided in table 10. As can be seen from this table, most of the tests have the expected trend that the increased elevation both delays the time required for the foam to reach the fire and makes the fires harder to extinguish since the foam on top of the blanket is drier and more fragile. Intuitively, the lower foam is wetter due to drainage from the foam above.

Table 10. Fire Location Comparison.

Test	Fire Scenario	Individual Fires	Extinguishment Time From Foam Start [sec]	Extinguishment Time From Foam Arrival [sec]
Deck Level				
Ansul 11	2 Sprays - Deck Level	1.8 MW Diesel Spray	245	215
		5.8 MW Heptane Spray	245	215
Buckeye 5	Vertical Diesel Spray - Deck Level	1.8 MW Diesel	42	12
Buckeye 7	Horizontal Heptane Spray - Deck Level	2 MW Heptane Spray	87	57
Buckeye 6	Horizontal Heptane Spray - Deck Level	5.8 MW Heptane Spray	370	340
Top of Mockup				
Ansul 9	Scenario 2A	.25 m^2 Heptane Pan	60	30
		1.8 MW Diesel Spray	No Ext	No Ext
		5.8 MW Heptane Spray	No Ext	No Ext
Buckeye 8	Vertical Diesel Spray - Top of Mockup	1.8 MW Diesel Spray	140	32
Buckeye 9	Horizontal Heptane Spray - Top of Mockup	2 MW Heptane Spray	330	222
Buckeye 10	Horizontal Heptane Spray - Top of Mockup	5.8 MW Heptane Spray	370	262

The larger heptane spray fires deviated from this trend by producing faster extinguishment times on top of the mockup than at deck level (relative to foam arrival). The closeness of the fire to the top of the compartment (e.g., the fire was located in the hot gas layer containing reduced oxygen concentration) may have resulted in this deviation (the lower oxygen concentrations may have made these fires less stable).

10.3.3 Foam Generation Using Inside Air

During these tests, using the products of combustion (inside air) to produce the foam significantly reduced the capabilities of the system. The degradation in capabilities is shown in the results presented in table 11.

Table 11. Comparison of Results Using Inside and Outside Air.

Test	Fire Scenario	Individual Fires	Extinguishment Time [sec]
Inside Air			
Chemguard 3	Scenario 4	4 m^2 Diesel Pan	65
Chemguard 4	Scenario 3	2 m^2 Diesel Pan	405
		Wood Crib	130
		1.1 MW Heptane Spray	630
Chemguard 5	Horizontal Heptane Spray - Deck Level	5.8 MW Heptane Spray	No Ext
Outside Air			
Chemguard 8	Scenario 4	4 m^2 Diesel Pan	35
Chemguard 7	Scenario 3	2 m^2 Diesel Pan	95
		Wood Crib	65
		1.1 MW Heptane Spray	195
Chemguard 9	Horizontal Heptane Spray - Deck Level	5.8 MW Heptane Spray	205

The initial tests were conducted using inside air (products of combustion). The hot smokey gases were observed to significantly impact the system's ability to make foam. During the tests conducted with diesel fuel (namely Scenario 4), the foam had the consistency of foam shaving cream. During the tests conducted with the larger fires (and consequently higher gas temperatures), the foam was very light and dry. In both cases, the fill rate and expansion ratio was significantly reduced. During the cold discharge test, the system produced foam with an expansion ratio on the order of 250:1 and filled the compartment at a rate of 1.5 m/min. During the test conducted with inside air against Scenario 4, these quantities, were reduced by almost an order of magnitude (fill rate = 0.15 m/min and expansion ratio = 30:1).

During this evaluation, the Chemguard HEFFSS was tested against the three fire scenarios required in MSC/Circ. 848 (using both inside and outside air). Since the fires in Scenario 2A were the same height in the compartment as the foam generators (and using inside air prevents the generators from filling the box with foam above the height the generators are installed), the large 5.8 MW heptane spray fire in Scenario 2A was moved to deck level.

For comparison purposes, the Chemguard HEFFSS using outside air was capable of extinguishing all of the test fires in about four minutes or less.

During the tests conducted with inside air, the Chemguard HEFFSS was only capable of extinguishing two of the three fire scenarios required by MCS circ. 848 (Scenario 3 and 4). The Chemguard HEFFSS using inside air could not extinguish the large spray fire combination in Scenario 2A. The extinguishment times for these fires was about twice as long as those observed when the system was tested using outside air.

10.4 System Requirements

There are two IMO test protocols applicable to HEFFSS in commercial ship machinery space applications. These protocols include a fire test described in MSC circ. 670 and a chemical compatibility test (compatibility with salt water) in MSC circ. 582. Although the requirements of MSC/Circ. 582 may apply, the test setup, HEFFSS hardware and fire scenario in (MSC/Circ. 670) are not in any way representative of the conditions and hazards of a shipboard machinery space.

There are currently two design constraints placed on HEFFSS in Chapter 6 of the FSS Code. These include a minimum fill rate of 1 meter per minute and a maximum expansion ratio of 1000:1. There appears to be no technical justification for these requirements. A detailed discussion of these issues is provided in the following sections.

10.4.1 Test Protocol

Since the current test protocol (MSC/Circ. 670) is not representative of machinery space applications and hazards, the gaseous agent protocol (MSC/Circ. 848) was selected as the basis for this evaluation.

The gaseous agent test protocol (MSC/Circ. 848) consists of four tests. The first test is an agent distribution test conducted against small fires located in the corners of the compartment and was not conducted during this evaluation. The remaining three tests consist of combinations of spray, pan and wood crib fires allowing an assessment of the HEFFSS against a range of fire sizes, types, and locations (elevations and degrees of obstruction) all representative of typical machinery space hazards. Based on the results of these tests, parameters of MSC/Circ. 848

appear to provide sufficient challenge and range to adequately test HEFFSS for machinery space applications.

The difficulty observed in extinguishing spray fires and conversely, the ease in extinguishing the pan fires, demonstrates that the current high expansion foam test protocol (MSC/Circ. 670) is inadequate for approving HEFFSS for machinery space applications. The single pan fire test required in MSC/Circ. 670 does not pose a challenge to HEFFSS. The primary hazard associated with machinery space applications (spray fires) is not even addressed by the protocol. As a result, it is recommended that HEFFSS be approved using the fire tests described in MSC/Circ. 848 rather than MSC/Circ. 670.

When adapting MSC/Circ. 848 for use with HEFFSS, some of the test parameters will need to be revised/modified to account for the differences (namely discharge times) between high expansion foam and gaseous agent technologies. These differences need to be reflected in both the fill time and extinguishment time requirements of the system.

The minimum fill rate requirement of 1 m/min stated in SOLAS/FSS Code needs to be abandoned for a new approach since it does not insure an acceptable level of performance and does not properly address spaces with vastly different ceiling heights. It also does not account for variations in extinguishing capabilities between HEFFSS. A maximum fill time is a better approach to this requirement and is the approach used in NFPA 11A (1999). Consistent with NFPA 11A, a two minute maximum fill time is recommended for this application (NFPA 11A requires a two minute fill time for unprotected steel compartments containing low flashpoint fuels). This is also the maximum discharge time allowed under MSC/Circ. 848 for inert gas extinguishing systems (if the intent is to keep things somewhat consistent between technologies).

A five-minute extinguishment time requirement (five minutes after the start discharge) is also recommended for these systems. This is longer than the gaseous agent system requirements (fires are required to be extinguished within 30 seconds after the end of discharge) but less than the 15 minutes requirement placed on water mist systems in MSC/Circ. 668/728. Based on the results of these tests, the five-minute requirement is challenging and will allow the distinction between higher and lower performance systems. The five-minute extinguishment time

requirement is acceptable from an exposure standpoint since the fill time requirement of two minutes will quickly reduce the overall exposures in the compartment regions close to the fire source/location.

This five-minute extinguishment time requirement is shown in table 12 along with the results of these tests. As shown in this table, only one of the systems as tested met the five minute requirement (Chemguard). This is primarily the result of the slower fill rates/longer fill times used during these tests. In short, the systems as tested are undersized or borderline based on these recommended requirements.

Table 12. Extinguishment Time Summary.
(all tests conducted using outside air)

Fire Scenario	Individual Fires	Extinguishment Times (sec)			
		Ansul	Buckeye	Chemguard	Proposed Requirement
2A	0.25m^2 Heptane Pan	65, 55, 60	66	30	300
	1.8 MW Diesel Spray	No, 590, No	430	245	300
	5.8 MW Heptane Spray	No, 590, No	430	245	300
3	2m^2 Diesel Pan	59,20	15	95	300
	Wood Crib	164, 200	30	65	300
	1.1 MW Heptane Spray	No, No	430	195	300
4	4m^2 Diesel Pan	60	55	65	300

No = No extinguishment

However, based on the results of these tests, it appears that the Buckeye HEFFSS would have met the extinguishment requirement using a higher fill rate/faster fill time. This statement is based on the time it took the system to extinguish the test fires after the foam had reached the fire. The results are inconclusive for the Ansul system.

The test protocol needs to have a means for accurately determining that extinguishment has occurred. The single thermocouple per fire in MSC/Circ. 848 did not handle displacement of the flame by the foam. Cameras were insufficient for determining extinguishment as they were obscured by the foam. Perhaps an array of thermocouples around each fire might suffice. More work is needed in this area.

10.4.2 SOLAS/FSS Code Requirements

It is recommended that the system parameters defined in the SOLAS/FSS Code be replaced by an approval test. With that said, the system should be installed as tested (i.e., fill rate, foam quality (concentrate, expansion ratio and drainage time) and type of air used to make the foam (inside air versus outside air)).

10.5 Technical Issues/Discussion

Although the results of these tests demonstrate the potential for using HEFFSS to protect shipboard machinery spaces, there is additional information that needs to be collected in order to fully understand the capabilities and limitations of these systems for this application. The areas requiring further research include the mechanisms of extinguishment, and how foam quality affects the capabilities of the system.

The scale of these tests prevented a detailed technical assessment of the mechanisms of extinguishment. However, some of the observations from these tests provide information about what may be occurring during the extinguishment process.

As the foam flows across the surface of the pan fires, it probably attenuates the radiation from the flame back to the fuel surface (reducing the pyrolysis rate) and seals/confines the vapors within the fuel (or narrow region above the fuel surface). There may also be some surface (fuel) cooling effects provided by the foam. The spray fires, on the other hand, are much more complicated.

The spray fires are probably extinguished by a combination of mechanisms. As the foam is entrained into the flame, the liquid in the foam may cool the flame similar to one of the

mechanisms of extinguishment associated with water mist (gas phase cooling/flame cooling). However, there is not enough liquid in the foam for this to be the primary mechanism of extinguishment. The other mechanisms are associated with reducing the oxygen available for combustion. The foam may confine the products of combustion to the region near the flame reducing the oxygen concentration in the gases being entrained by the fire. The viscosity/strength of the foam may also impede the entrainment of air into the flame. The contribution of these three mechanisms is probably a function of both the fire conditions (fire size/heat release rate, fuel type, and fire location) and the characteristics of the system (foam quality, expansion ratio and fill rate).

Understanding these mechanisms may explain how a small fire can potentially continue to exist under the foam blanket for extended periods of time (minutes) during the extinguishment of the heptane spray fires (as observed during a limited number of these tests). The existence of these undetectable small flames/fires within the foam blanket is a serious concern and needs to be considered when re-entering/reclaiming the space after the fire appears to be extinguished.

Understanding how foam quality affects the extinguishment process and the capabilities and limitations of these HEFFSS is also desired. This understanding should include not only the conditions required to extinguish a fire but also how the foam quality varies with foam depth/height and time. Foam depth/height parameters are important when considering these systems for very large/tall machinery spaces. Conceptually, there should be a critical height in which the foam can be stacked. This critical height is associated with the strength characteristics of the foam. When filling a tall space with foam, there should be a point/height where the weight of the foam added compresses the lower foam preventing any further filling of the space. This issue was not addressed during this evaluation. Also, the foam drainage time (how the foam degrades over time) is an important parameter associated with re-entry into the space that needs to be considered when developing firefighting doctrine.

11.0 SUMMARY

A total of 35 tests were conducted in this evaluation utilizing the equipment and foam concentrates from three manufacturers: Ansul, Buckeye and Chemguard. Each manufacturer

was responsible for the design of their respective system. These designs were based on the minimum SOLAS/FSS Code requirements plus some additional capacity to provide a factor of safety for these tests. All of the manufacturers/systems included in this evaluation produced foams with expansion ratios on the order of 300:1 and fill rates on the order of 1.6 m/min.

All of the systems easily extinguished the pan fires included in this evaluation independent of the type of fuel (heptane or diesel). The differences in system capabilities were observed during the extinguishment of the spray fires (namely the heptane spray fires). The heptane spray fires presented a major challenge to the HEFFSS and in some cases, were not extinguished.

During the tests conducted with the heptane spray fires, the extinguishment times were in many cases two to three times longer than it took to fill the compartment with foam during the cold discharge tests. Although the fire was consuming some of the foam, a significant amount was observed flowing out of all of the openings in the compartment by the end of the test. Under certain conditions, there appears to be the need to compress the foam (making it denser and/or wetter) in order to extinguish the heptane spray fires. It is unknown whether this observation has any implication on HEFFSS capabilities in extremely large (tall) machinery spaces.

With respect to the individual systems, there were variations in the fire suppression capabilities and/or foam quality between the three manufactures. The Buckeye and Chemguard systems produced more robust foam and were both capable of extinguishing the heptane spray fires. The foam produced by these two systems was so robust (i.e., hard to break down) that the space needed to be cleaned using a defoaming agent after each test. The Ansul foam was more fragile and had difficulty extinguishing the heptane spray fires. During cleanup, the Ansul foam was quickly broken down/washed away using short bursts of water. It is unknown whether the difficulty in extinguishing the heptane spray fires was associated with the foam concentrate, foam generating equipment or both.

The results of these tests demonstrate the potential for using HEFFSS for protecting shipboard machinery spaces. Additional research is required in specific areas to fully understand the capabilities and limitations of these systems. Areas requiring further research include

understanding the mechanisms of extinguishment, and the effects of foam quality on the capabilities of the system.

It is recommended that the system parameters (a minimum fill rate of 1 meter per minute and a maximum expansion ratio of 1000:1) defined in SOLAS/FSS Code be replaced by an approval test (a modified version of MSC/Circ. 848 is recommended for this application).

Based on our current knowledge, the parameters of MSC/Circ. 848 appear to provide sufficient challenge and range to adequately test these systems against conditions likely in a machinery space fire. The difficulty observed in extinguishing spray fires and conversely, the ease in extinguishing the pan fires, demonstrates that the current high expansion foam test protocol (MSC/Circ. 670) is inadequate for approving HEFFSS for machinery space applications. As a result, it is recommended that a modified version of MSC/Circ. 848 serve as the basis for approving HEFFSS for machinery space applications.

The new protocol will need to account for the differences between high expansion foam and gaseous agent technologies (namely discharge times). These differences need to be reflected in both the fill rate and extinguishment time requirements of the system. A maximum fill time of two minutes and an extinguishment time of five minutes or less is recommended for this application/technology. The protocol will need additional instrumentation to ensure accurate determination of extinguishment of fires due to the displacement of flames by the foam. Additional modifications may also be required once the mechanisms of extinguishment and foam quality issues are better understood.

12.0 REFERENCES

Ingason, H (1992). Foam Sprinklers as a Replacement for Halon in Engine Rooms. Swedish National Testing and Research Institute, SP Report 1992:37.

International Maritime Organization (1992). Guidelines for the Performance and Testing Criteria and Surveys of Low-Expansion Foam Concentrates for Fixed Fire-Extinguished Systems (MSC Circular 582). London, England.

International Maritime Organization (1994). Alternative Arrangements For Halon Fire-Extinguishing Systems In Machinery Spaces and Pump-Rooms (IMO FP39 MSC Circular 668). London, England.

International Maritime Organization (1995). Guidelines for the Performance and Testing Criteria and Surveys of High-Expansion Foam Concentrates for Fixed Fire-Extinguishing Systems (MSC Circular 670). London, England.

International Maritime Organization (1998). Revised guidelines for Approval of Equivalent Fixed Gas Fire Extinguishing Systems, As Referred to in SOLAS 74, for Machinery Spaces and Cargo Pump Rooms (IMO) FP42 MSC Circular 848). London, England.

International Maritime Organization (2001). Guidelines for the Approval of Fixed Aerosol Fire Extinguishing Systems as Referred to in SOLAS 74, for Machinery Spaces (IMO FP44 MSC Circular 1003). London, England.

International Maritime Organization (2001a). International Convention for The Safety of Life At Sea (SOLAS 74). London, England.

International Maritime Organization (2001b). International Code for Fire Safety Systems. London, England.

NFPA 11A (1999). Standard for Medium and High Expansion Foam Systems. National Fire Protection Associates, Quincy, MA.

APPENDIX A - IMO TEST PROTOCOL

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REVISED GUIDELINES FOR THE APPROVAL OF EQUIVALENT FIXED GAS FIRE-EXTINGUISHING SYSTEMS, AS REFERRED TO IN SOLAS 74, FOR MACHINERY SPACES AND CARGO PUMP-ROOMS

1 The Maritime Safety Committee, at its sixty-seventh session (2 to 6 December 1996), approved Guidelines for the approval of equivalent fixed gas fire-extinguishing systems, as referred to in SOLAS 74, for machinery spaces and cargo pump-rooms, as MSC/Circ.776.

2 The Sub-Committee on Fire Protection, at its forty-second session (8 to 12 December 1997), recognized the need of technical improvement to the Guidelines contained in MSC/Circ.776 to assist in their proper implementation and, to that effect, prepared amendments to the Guidelines.

3 The Committee, at its sixty-ninth session (11 to 20 May 1998), approved revised Guidelines for the approval of equivalent fixed gas fire-extinguishing systems, as referred to in SOLAS 74, for machinery spaces and cargo pump-rooms, as set out in the annex, to supersede the Guidelines attached to MSC/Circ.776.

4 Member Governments are invited to apply the annexed Guidelines when approving equivalent fixed gas fire-extinguishing systems for use in machinery spaces of category A and cargo pump-rooms.

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ANNEX

REVISED GUIDELINES FOR THE APPROVAL OF EQUIVALENT FIXED GAS FIRE-EXTINGUISHING SYSTEMS, AS REFERRED TO IN SOLAS 74, FOR MACHINERY SPACES AND CARGO PUMP-ROOMS

General

1 Fixed gas fire-extinguishing systems for use in machinery spaces of category A and cargo pump-rooms equivalent to fire-extinguishing systems required by SOLAS regulations II-2/7 and II-2/63 should prove that they have the same reliability which has been identified as significant for the performance of fixed gas fire-extinguishing systems approved under the requirements of SOLAS regulation II-2/5. In addition, the system should be shown by test to have the capability of extinguishing a variety of fires that can occur in a ship's engine-room.

Principal requirements

2 All requirements of SOLAS regulations II-2/5.1, 5.3.1, 5.3.2 to 5.3.3, except as modified by these guidelines, should apply.

3 The minimum extinguishing concentration should be determined by a cup burner test acceptable to the Administration. The design concentration should be at least 20% above the minimum extinguishing concentration. These concentrations should be verified by full-scale testing described in the test method, as set out in the appendix.

4 For systems using halocarbon clean agents, 95% of the design concentration should be discharged in 10 s or less. For inert gas systems, the discharge time should not exceed 120 s for 85% of the design concentration.

5 The quantity of extinguishing agent for the protected space should be calculated at the minimum expected ambient temperature using the design concentration based on the net volume of the protected space, including the casing.

5.1 The net volume of a protected space is that part of the gross volume of the space which is accessible to the free extinguishing agent gas.

5.2 When calculating the net volume of a protected space, the net volume should include the volume of the bilge, the volume of the casing and the volume of free air contained in air receivers that in the event of a fire is released into the protected space.

5.3 The objects that occupy volume in the protected space should be subtracted from the gross volume of the space. They include, but are not necessarily limited to:

- auxiliary machinery;
- boilers;
- condensers;
- evaporators;
- main engines;
- reduction gears;

- tanks; and
- trunks.

5.4 Subsequent modifications to the protected space that alter the net volume of the space shall require the quantity of extinguishing agent to be adjusted to meet the requirements of this paragraph and paragraph 6.

6 No fire suppression agent should be used which is carcinogenic, mutagenic, or teratogenic at concentrations expected during use. No agent should be used in concentrations greater than the cardiac sensitization NOAEL (No Observed Adverse Effect Level), without the use of controls as provided in SOLAS regulations II-2/5.2.5.1 and 5.2.5.2. In no case should an agent be used above its LOAEL (Lowest Observed Adverse Effects Level) nor ALC (Approximate Lethal Concentration) calculated on the net volume of the protected space at the maximum expected ambient temperature.

7 The system and its components should be suitably designed to withstand ambient temperature changes, vibration, humidity, shock, impact, clogging, and corrosion normally encountered in machinery spaces or cargo pump-rooms in ships.

8 The system and its components should be designed and installed in accordance with international standards acceptable to the Organization[1] and manufactured and tested to the satisfaction of the Administration. As a minimum, the design and installation standards should cover the following elements:

.1 safety:

- toxicity;
- noise, nozzle discharge; and
- decomposition products;

.2 storage container design and arrangement:

- strength requirements;
- maximum/minimum fill density, operating temperature range;
- pressure and weight indication;
- pressure relief; and
- agent identification and lethal requirements;

.3 agent supply, quantity, quality standards;

.4 pipe and fittings:

- strength, material, properties, fire resistance; and
- cleaning requirements;

[1]Until international standards are developed, national standards acceptable to the Administration should be used. Available national standards include, e.g., Standards of Australia, the United Kingdom and NFPA 2001.

.5 valves:

- testing requirements;
- corrosion resistance; and
- elastomer compatibility;

.6 nozzles:

- height and area testing requirements; and
- corrosion and elevated temperature resistance;

.7 actuation and control systems:

- testing requirements; and
- backup power requirements;

.8 alarms and indicators:

- predischarge alarm, agent discharge alarms as time delays;
- abort switches;
- supervisory circuit requirements; and
- warning signs and audible and visual alarms should be located outside each entry to the relevant space as appropriate;

.9 agent flow calculation:

- approval and testing of design calculation method; and
- fitting losses and/or equivalent length;

.10 enclosure integrity and leakage requirements:

- enclosure leakage;
- openings; and
- mechanical ventilation interlocks;

.11 design concentration requirements, total flooding quantity;

.12 discharge time; and

.13 inspection, maintenance, and testing requirements.

9 The nozzle type, maximum nozzle spacing, maximum height and minimum nozzle pressure should be within limits tested to provide fire extinction per the proposed test method.

10 Provisions should be made to ensure that escape routes which are exposed to leakage from the protected space are not rendered hazardous during or after discharge of the agent. Control stations and other locations that require manning during a fire situation should have provisions to keep HF and HCl below 5 ppm at that location. The concentrations of other products should be kept below concentrations considered hazardous for the required duration of exposure.

11 Agent containers may be stored within a protected machinery space if the containers are distributed throughout the space and the provisions of SOLAS regulation II-2/5.3.3 are met. The arrangement of containers and electrical circuits and piping essential for the release of any system should be such that in the event of damage to any one power release line through fire or explosion in the protected space, i.e. a single fault concept, at least five-sixths of the fire-extinguishing charge as required by paragraph 5 of this annex can still be discharged having regard to the requirement for uniform distribution of medium throughout the space. The arrangements in respect of systems for spaces requiring less than 6 containers should be to the satisfaction of the Administration.

12 A minimum agent hold time of 15 min should be provided.

13 The release of an extinguishing agent may produce significant over and under pressurization in the protected space. Measures to limit the induced pressures to acceptable limits should be provided.

14 For all ships, the fire-extinguishing system design manual should address recommended procedures for the control of products of agent decomposition. The performance of fire-extinguishing arrangements on passenger ships should not present health hazards from decomposed extinguishing agents, e.g., on passenger ships, the decomposition products should not be discharged in the vicinity of muster (assembly) stations.

APPENDIX

TEST METHOD FOR FIRE TESTING OF FIXED GAS FIRE-EXTINGUISHING SYSTEMS

1 Scope

1.1 This test method is intended for evaluating the extinguishing effectiveness of fixed gas fire-extinguishing systems for the protection of machinery spaces of category A and cargo pump-rooms.

1.2 Fire-extinguishing systems presently covered in SOLAS regulation II-2/5, as amended, are excluded.

1.3 The test method covers the minimum requirements for fire-extinguishing.

1.4 This test method is applicable to gases, liquefied gases and mixtures of gases. The test method is not valid for extinguishant gases mixed with compounds in solid or liquid state at ambient conditions.

1.5 The test programme has two objectives: (1) establishing the extinguishing effectiveness of a given agent at its tested concentration, and (2) establishing that the particular agent distribution system puts the agent into the enclosure in such a way as to fully flood the volume to achieve an extinguishing concentration at all points.

2 Sampling

The components to be tested should be supplied by the manufacturer together with design and installation criteria, operational instructions, drawings and technical data sufficient for the identification of the components.

3 Method of test

3.1 Principle

This test procedure enables the determination of the effectiveness of different gaseous agent extinguishing systems against spray fires, pool fires and class A fires.

3.2 Apparatus

3.2.1 Test room

The tests should be performed in 100 m^2 room, with no horizontal dimension less than 8 m, with a ceiling height of 5 m. The test room should be provided with a closable access door measuring approximately 4 m^2 in area. In addition, closable ventilation hatches measuring at least 6 m^2 in total area should be located in the ceiling.

3.2.2 Integrity of test enclosure

The test enclosure is to be nominally leak tight when doors and hatches are closed. The integrity of seals on doors, hatches, and other penetrations (e.g., instrumentation access ports) must be verified before each test.

3.2.3 Engine mock-up

.1 An engine mock-up of size (width x length x height) 1 m x 3 m x 3 m should be constructed of sheet steel with a nominal thickness of 5 mm. The mock-up should be fitted with two steel tubes diameter 0.3 m and 3 m length that simulate exhaust manifolds and a solid steel plate. At the top of the mock-up a 3 m^2 tray should be arranged. See figures 1, 2 and 3.

.2 A floor plate system 4 m x 6 m x 0.75 m high shall surround the mock-up. Provision shall be made for placement of the fuel trays, described in table 1, and located as described in table 2.

3.2.4 Instrumentation

Instrumentation for the continuous measurement and recording of test conditions should be employed. The following measurements should be made:

.1 temperature at three vertical positions (e.g., 1, 2.5, and 4.5 m)

.2 enclosure pressure

.3 gas sampling and analysis, at mid-room height, for oxygen, carbon dioxide, carbon monoxide, and relevant halogen acid products, e.g., hydrogen iodide, hydrofluoric acid, hydrochloric acid

.4 means of determining flame-out indicators

.5 fuel nozzle pressure in the case of spray fire

.6 fuel flow rate in the case of spray fires

.7 discharge nozzle pressure

3.2.5 Nozzles

3.2.5.1 For test purposes, nozzles should be located within 1 m of the ceiling.

3.2.5.2 If more than one nozzle is used they should be symmetrically located.

3.2.6 Enclosure temperature

The ambient temperature of the test enclosure at the start of the test should be noted and serve as the basis for calculating the concentration that the agent would be expected to achieve at that temperature and with that agent weight applied in the test volume.

3.3 Test fires and programme

3.3.1 Fire types

The test programme, as described in table 3, should employ test fires as described in table 1.

Table 1
Parameters of Test Fires

Fire	Type	Fuel	Fire Size, MW	Remarks
A	76 - 100 mm ID Can	Heptane	0.0012 to 0.002	Tell tale
B	0.25 m^2 Tray	Heptane	0.35	
C	2 m^2 Tray	Diesel /Fuel Oil	3	
D	4 m^2 Tray	Diesel /Fuel Oil	6	
E	Low pressure spray	Heptane 0.16 ± 0.01 kg/s	5.8	
F	Low pressure, low flow spray	Heptane 0.03 ± 0.005 kg/s	1.1	
G	High pressure spray	Diesel /Fuel Oil 0.05 ± 0.002 kg/s	1.8	
H	Wood Crib	Spruce or Fir	0.3	See Note 2
I	0.10 m^2 tray	Heptane	0.14	

Notes to table 1:

1 Diesel/Fuel Oil means light diesel or commercial fuel oil.

2 The wood crib should be substantially the same as described in ISO/TC 21/SC5/WG 8 ISO Draft International Standard, *Gaseous fire extinguishing systems, Part 1: General Requirements*. The crib should consist of six, trade size 50 mm x 50 mm by 450 mm long, kiln dried spruce or fir lumber having a moisture content between 9% and 13%. The members should be placed in 4 alternate layers at right angles to one another. Members should be evenly spaced forming a square structure.

Achieve ignition of the crib by burning commercial grade heptane in a square steel tray 0.25 m^2 in area. During the pre-burn period the crib should be placed centrally above the top of the tray a distance of 300 to 600 mm.

Table 2
Spray fire test parameters

Fire type	Low pressure(E)	Low pressure, Low flow(F)	High pressure(G)
Spray nozzle	Wide spray angle (120 to 125°) full cone type	Wide spray angle (80°) full cone type	Standard angle (at 6 Bar) full cone type
Nominal fuel pressure	8 Bar	8.5 Bar	150 Bar
Fuel flow	0.16 ± 0.01 kg/s	0.03 ± 0.005 kg/s	0.050 ± 0.002 kg/s
Fuel temperature	20 ± 5°C	20 ± 5°C	20 ± 5°C
Nominal heat release rate	5.8 ± 0.6 MW	1.1 ± 0.1 MW	1.8 ± 0.2 MW

3.3.2.1 All applicable tests of table 3 should be conducted for every new fire extinguishant gas, or mixture of gases.

3.3.2.2 Only Test 1 is required to evaluate new nozzles and related distribution system equipment (hardware) for systems employing fire extinguishants that have successfully completed the requirements of 3.3.2.1. Test 1 should be conducted to establish and verify the manufacturer's minimum nozzle design pressure.

3.4 Extinguishing system

3.4.1 System installation

The extinguishing system should be installed according to the manufacturer's design and installation instructions. The maximum vertical distance should be limited to 5 m.

3.4.2 Agent

3.4.2.1 Design concentration

The agent design concentration is that concentration (in volume per cent) required by the system designer for the fire protection application.

3.4.2.2 Test concentration

The concentration of agent to be used in the fire extinguishing tests should be the design concentration specified by the extinguishing system manufacturer, except for Test 1 which should be conducted at 83% of the manufacturer's recommended design concentration but in no case at less than the cup burner extinguishing concentration.

3.4.2.3 Quantity of agent

The quantity of agent to be used should be determined as follows:

3.4.2.3.1 Halogenated agents

$$W = (V/S) \cdot C/(100 - C)$$

where:

W = agent mass, kg
V = volume of test enclosure, m^3
S = agent vapour specific volume at temperature and pressure of the test enclosure, kg/m^3
C = gaseous agent concentration, volume per cent.

3.4.2.3.2 Inert gas agents

$$Q = V\,[294/(273 + T)] \bullet (P/1.013) \bullet \ln[100/(100 - C)]$$

where:

- Q = volume of inert gas, measured at 294 K and 1.013 bar, discharged, m^3
- V = volume of test enclosure, m^3
- T = test enclosure temperature, Celsius
- P = test enclosure pressure, bar
- C = gaseous agent concentration, volume per cent.

3.5 Procedure

3.5.1 Fuel levels in trays

The trays used in the test should be filled with at least 30 mm fuel on a water base. Freeboard should be 150 ± 10 mm.

3.5.2 Fuel flow and pressure measurements

For spray fires, the fuel flow and pressure should be measured before and during each test.

3.5.3 Ventilation

3.5.3.1 Pre-burn period

During the pre-burn period the test enclosure should be well ventilated. The oxygen concentration, as measured at mid-room height, shall not be less than 20 volume per cent at the time of system discharge.

3.5.3.2 End of pre-burn period

Doors, ceiling hatches, and other ventilation openings should be closed at the end of the pre-burn period.

3.5.4 Duration of test

3.5.4.1 Pre-burn time

Fires should be ignited such that the following burning times occur before the start of agent discharge:

.1 sprays - 5 to 15 s
.2 trays - 2 min
.3 crib - 6 min

3.5.4.2 Discharge time

.1 halogenated agents should be discharged at a rate sufficient to achieve delivery of 95% of the minimum design quantity in 10 s or less.

.2 inert gas agents should be discharged at a rate sufficient to achieve 85% of the minimum design quantity in 120 s or less.

3.5.4.3 Soak time

After the end of agent discharge the test enclosure should be kept closed for 15 min.

3.5.5 Measurements and observations

3.5.5.1 Before test

.1 temperature of test enclosure, fuel and engine mock-up
.2 initial weights of agent containers
.3 verification of integrity agent distribution system and nozzles
.4 initial weight of wood crib.

3.5.5.2 During test

.1 start of the ignition procedure
.2 start of the test (ignition)
.3 time when ventilating openings are closed
.4 time when the extinguishing system is activated
.5 time from end of agent discharge
.6 time when the fuel flow for the spray fire is shut off
.7 time when all fires are extinguished
.8 time of re-ignition, if any, during soak period
.9 time at end of soak period
.10 at the start of test initiate continuous monitoring as per 3.2.4.

3.5.6 Tolerances

Unless otherwise stated, the following tolerances should apply:

.1	length	±2% of value
.2	volume	±5% of value
.3	pressure	±3% of value
.4	temperature	±5% of value
.5	concentration	±5% of value.

These tolerances are in accordance with ISO standard 6182/1, February 1994 edition [4].

4 Classification criteria

4.1 Class B fires must be extinguished within 30 s of the end of agent discharge. At the end of the soak period there should be no reignition upon opening the enclosure.

4.2 The fuel spray should be shut off 15 s after extinguishment. At the end of the soak time, the fuel spray should be restarted for 15 s prior to reopening the door and there should be no reignition.

4.3 At the end of the test fuel trays must contain sufficient fuel to cover the bottom of the tray.

4.4 Wood crib weight loss must be no more than 60%.

5 Test report

The test report should include the following information:

.1 name and address of the test laboratory;
.2 date and identification number of the test report;
.3 name and address of client;
.4 purpose of the test;
.5 method of sampling system components;
.6 name and address of manufacturer or supplier of the product;
.7 name or other identification marks of the product;
.8 description of the tested product;
- drawings
- descriptions
- assembly instructions
- specification of included materials
- detailed drawing of test set-up;

.9 date of supply of the product;
.10 date of test;
.11 test method;
.12 drawing of each test configuration;
.13 identification of the test equipment and used instruments;
.14 conclusions;
.15 deviations from the test method, if any;
.16 test results including measurements and observations during and after the test; and
.17 date and signature.

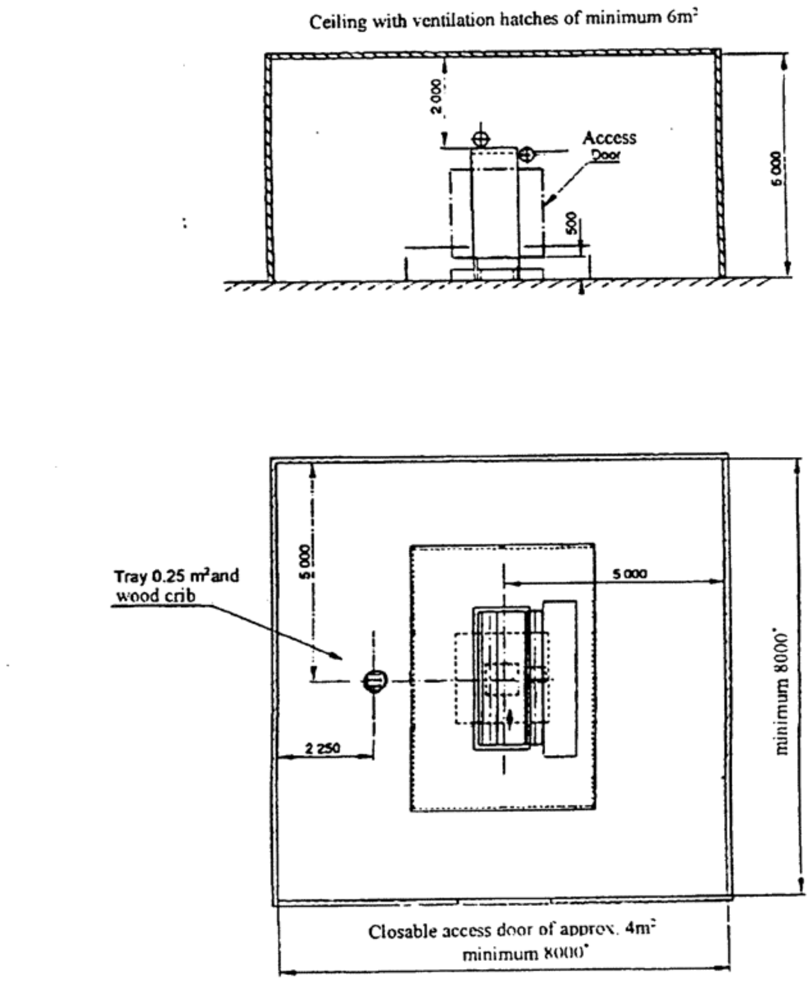


Figure 1

*The area should be $100m^2$

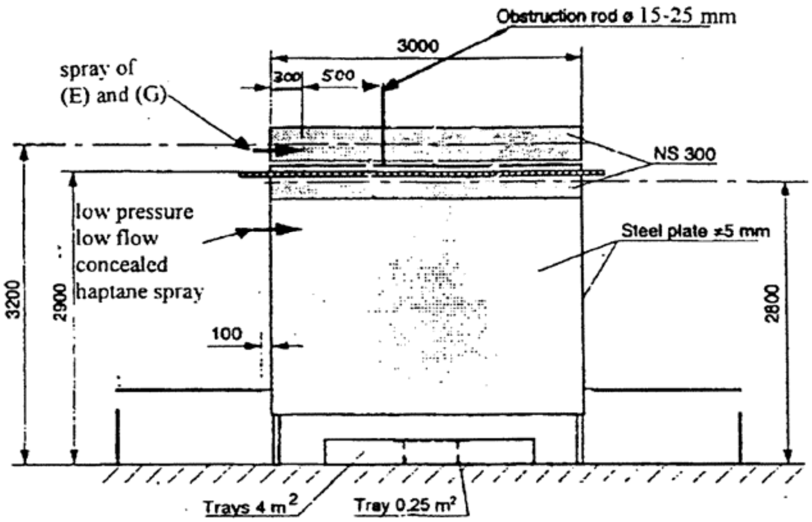
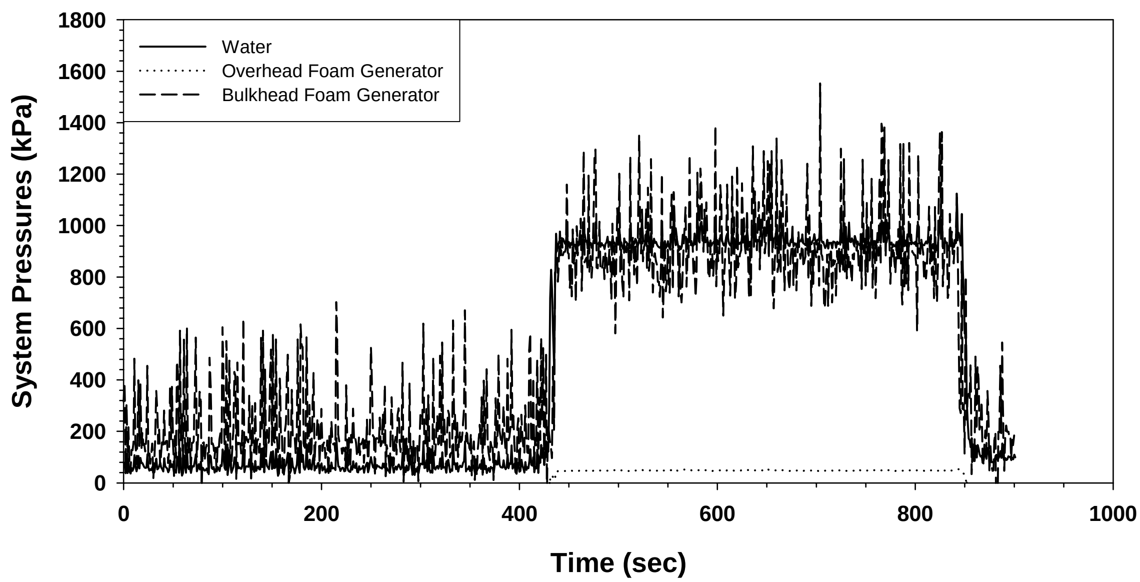

Obstruction rod ø 15-25 mm
3000
300
500
spray of
(E) and (G)
NS 300
low pressure
low flow
concealed
haptane spray
Steel plate ±5 mm
3200
2900
2800
100
Trays 4 m2
Tray 0.25 m2

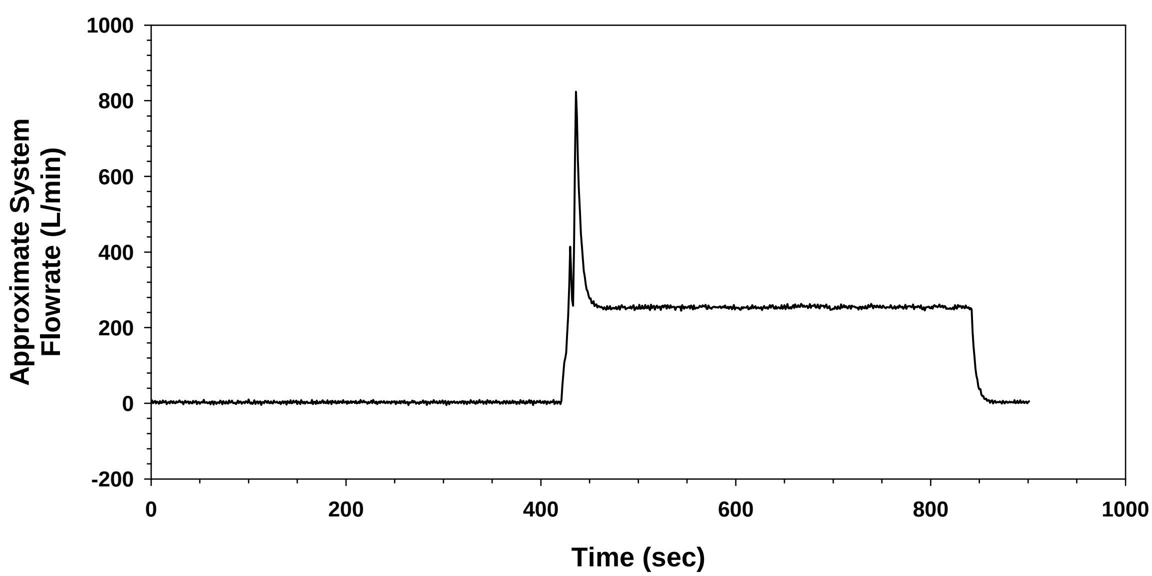
Figure 3

APPENDIX B - TEST DATA

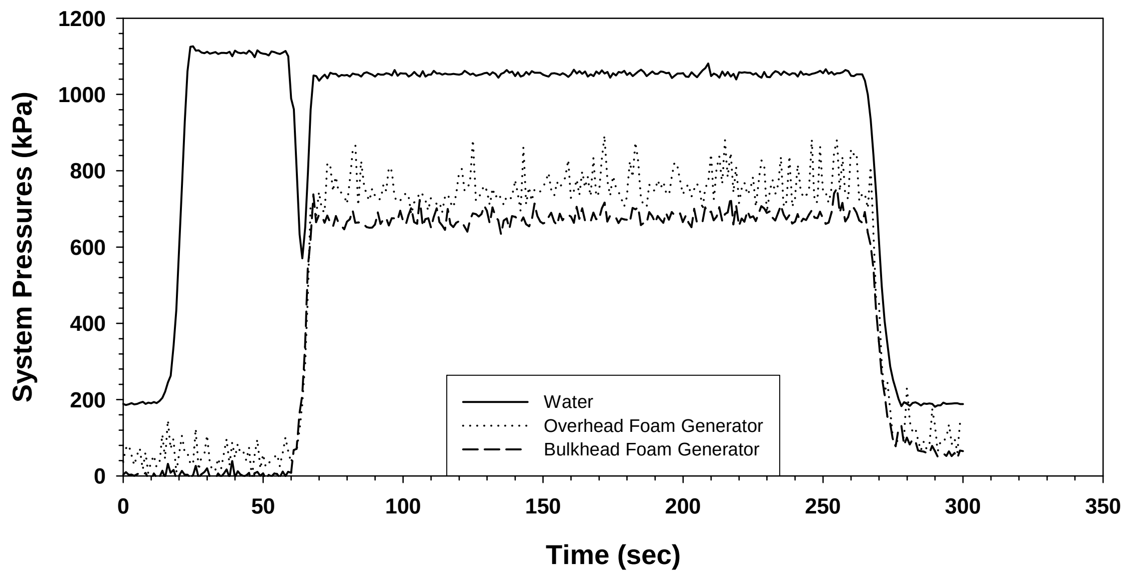
Ansul Test 1 - Cold Discharge



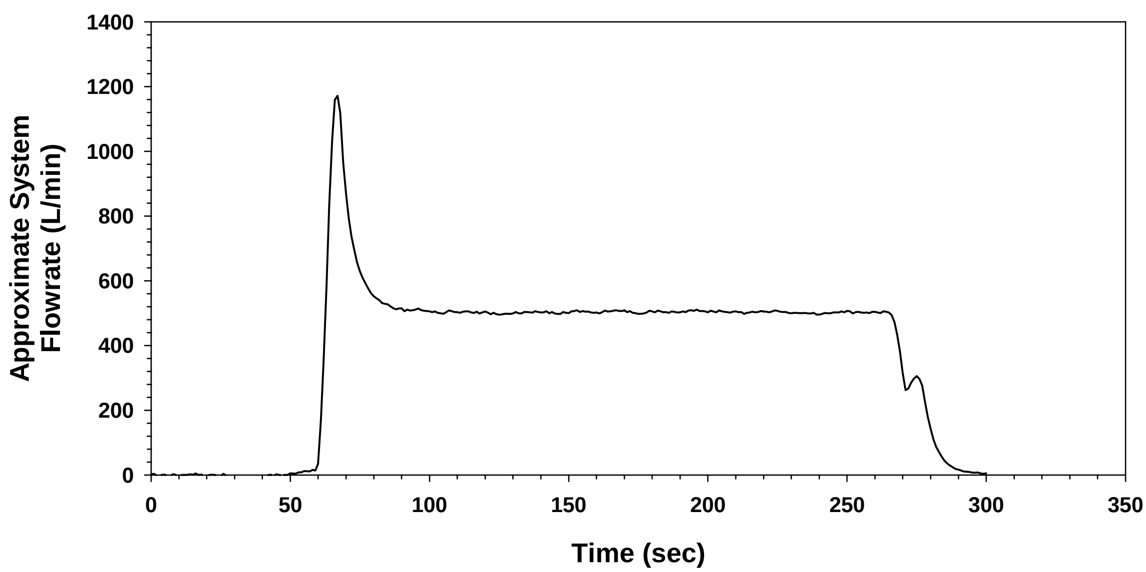
Ansul Test 1 - Cold Discharge



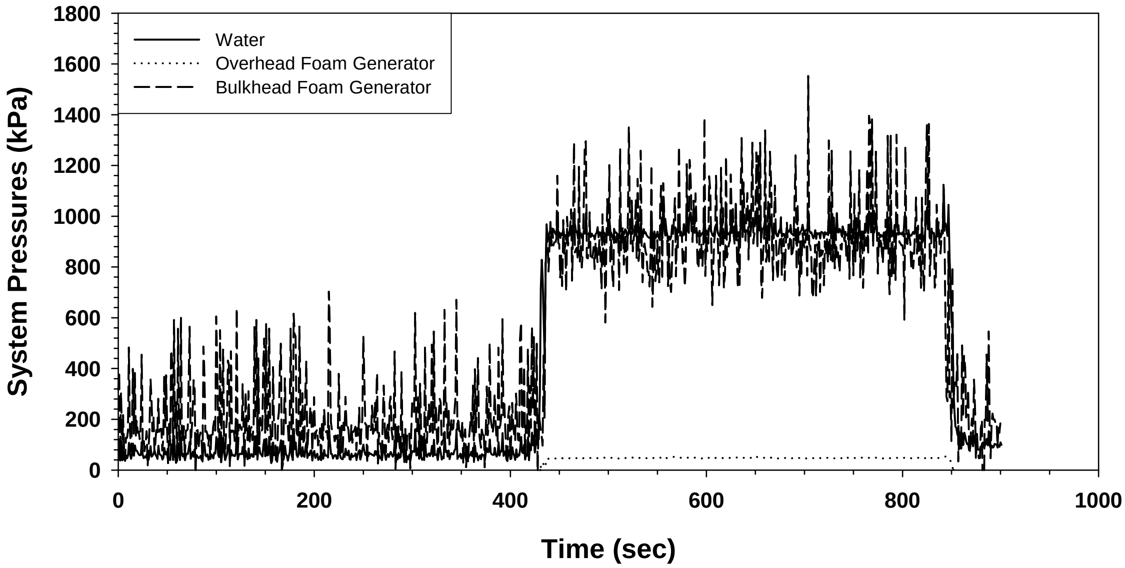
Ansul Test 2 - Cold Discharge



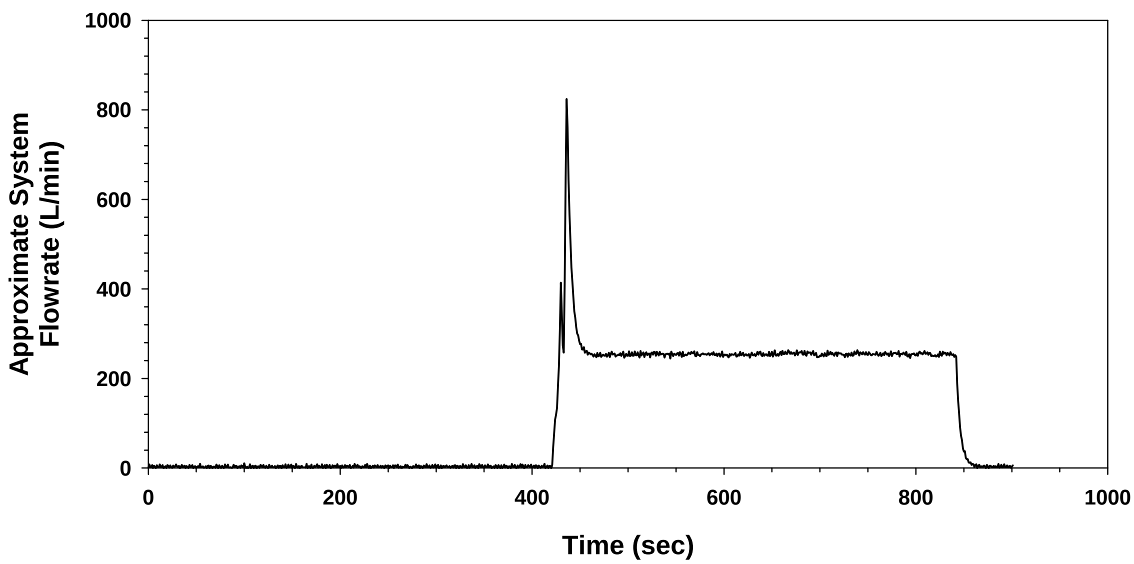
Ansul Test 2 - Cold Discharge



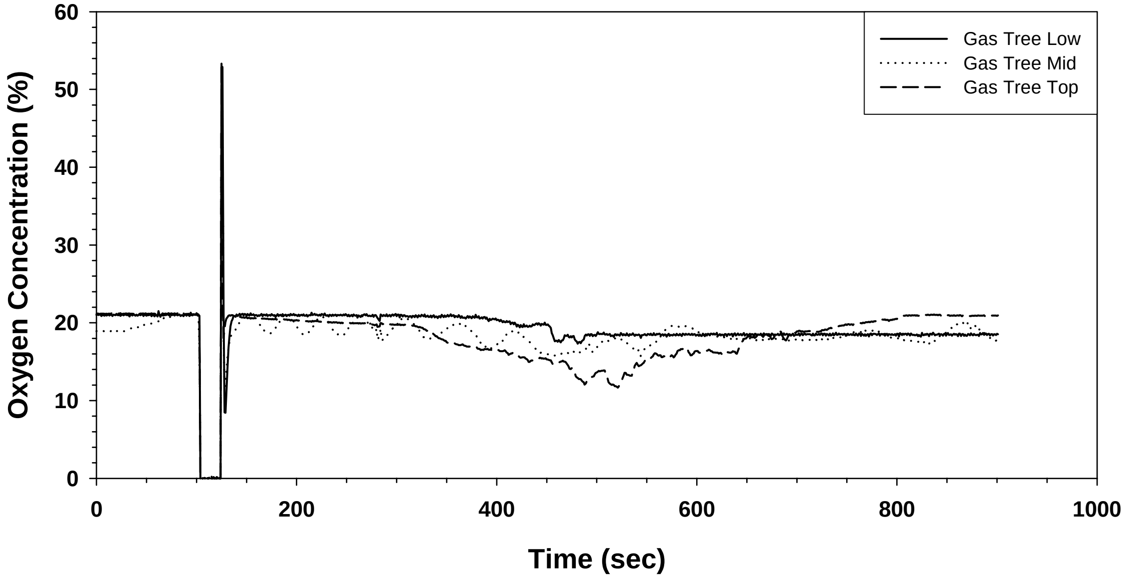
Ansul Test 3 - Scenario 3



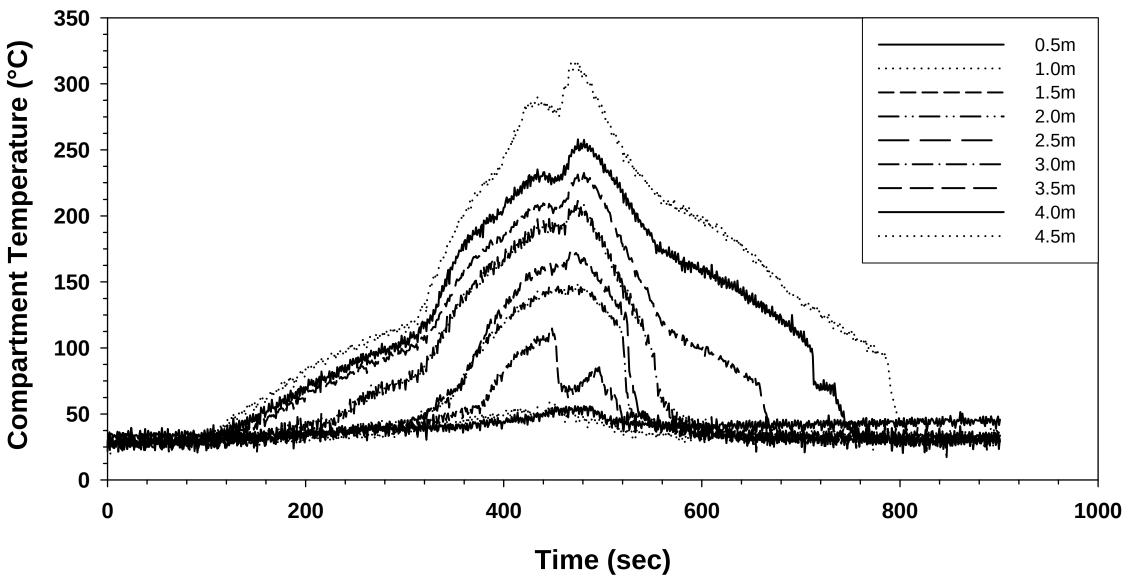
Ansul Test 3 - Scenario 3

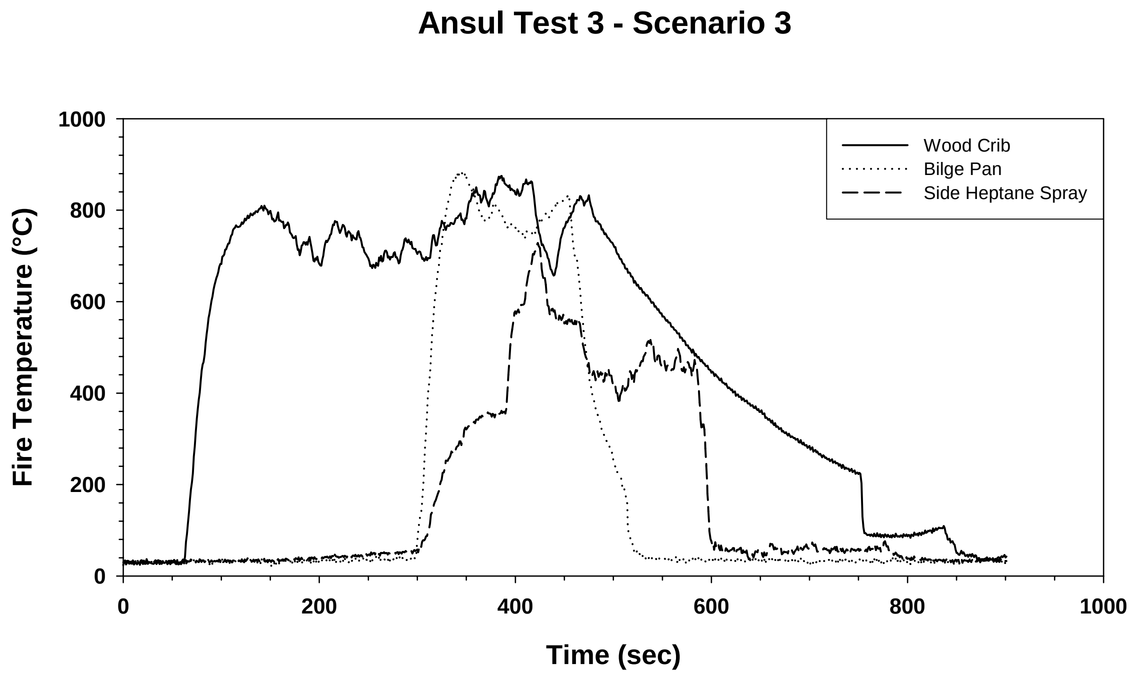


Ansul Test 3 - Scenario 3

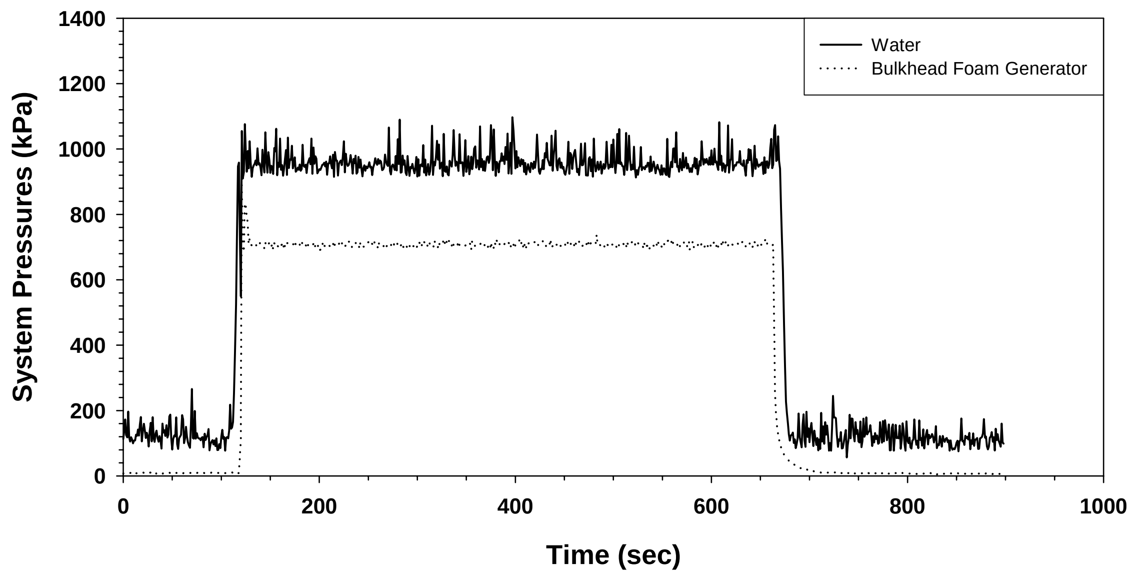


Ansul Test 3 - Scenario 3

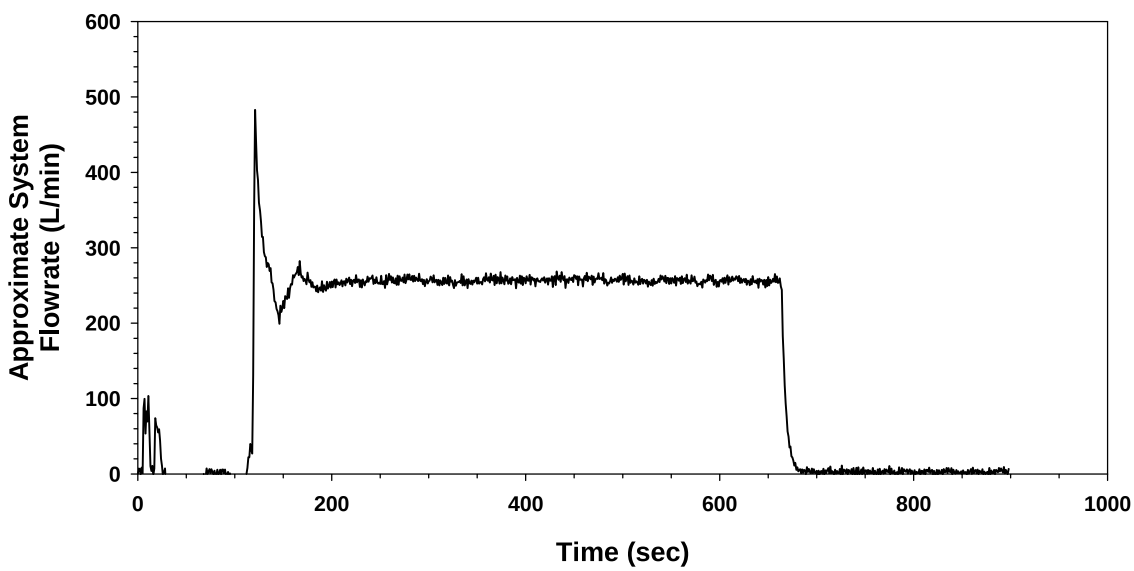



Ansul Test 3 - Scenario 3
Fire Temperature (°C)
Time (sec)
Wood Crib
Bilge Pan
Side Heptane Spray
0
200
400
600
800
1000

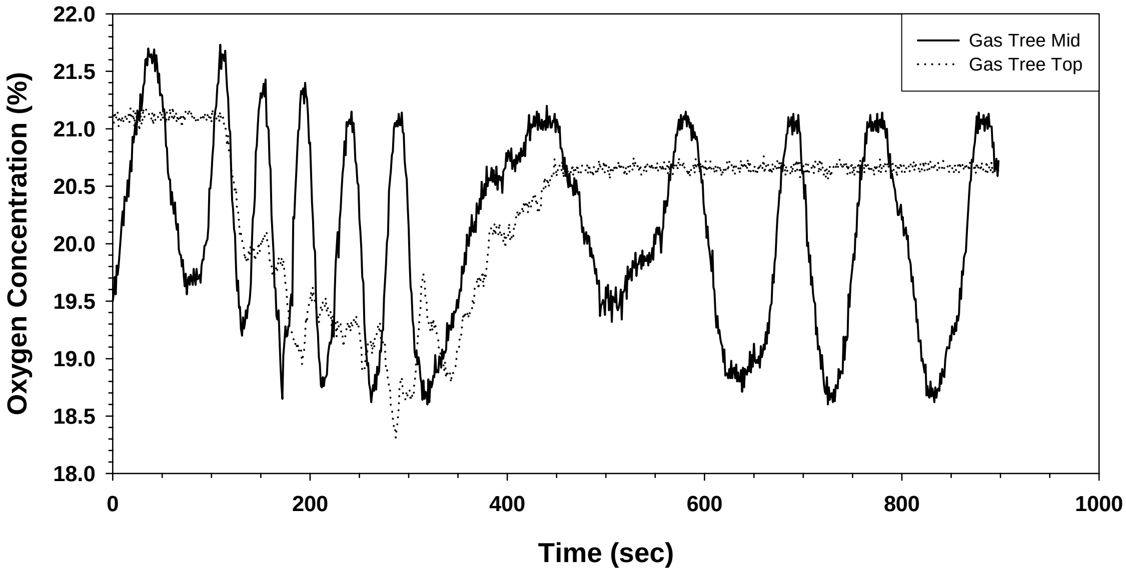
Ansul Test 4 - Heptane Spray on Side



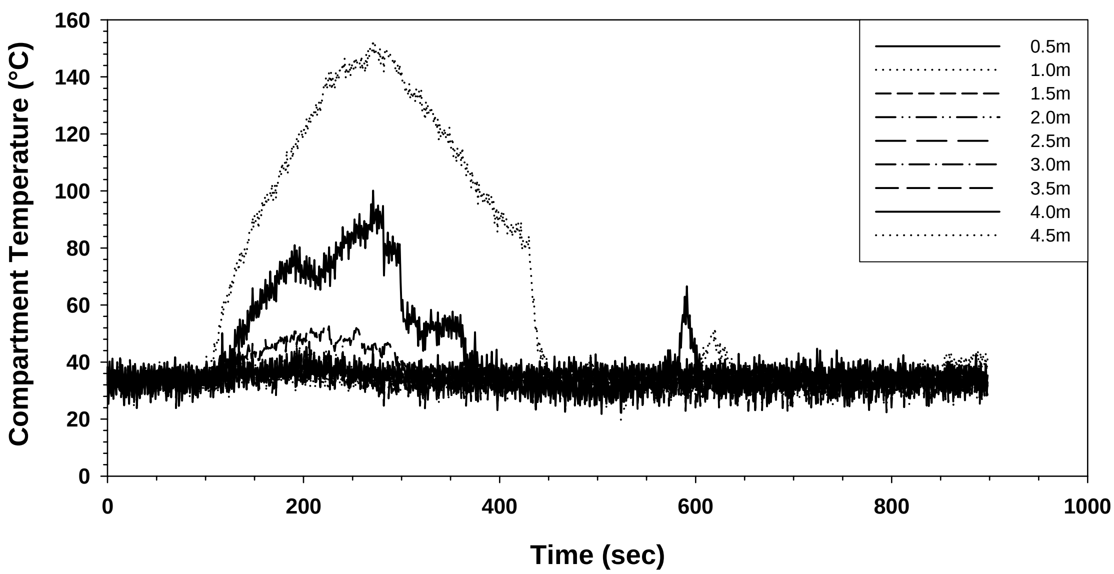
Ansul Test 4 - Heptane Spray on Side



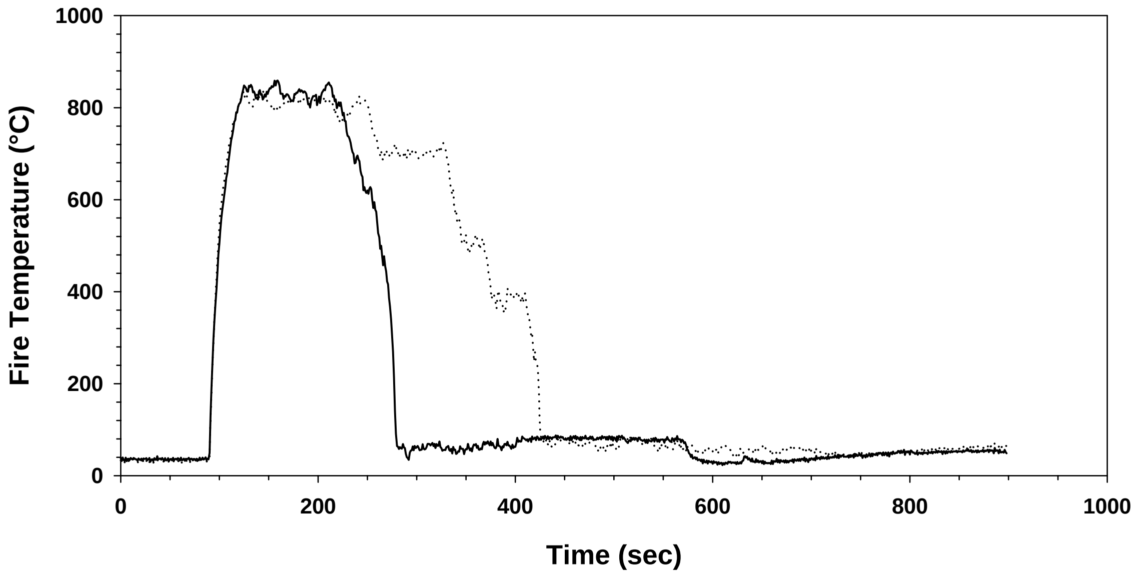
Ansul Test 4 - Heptane Spray on Side



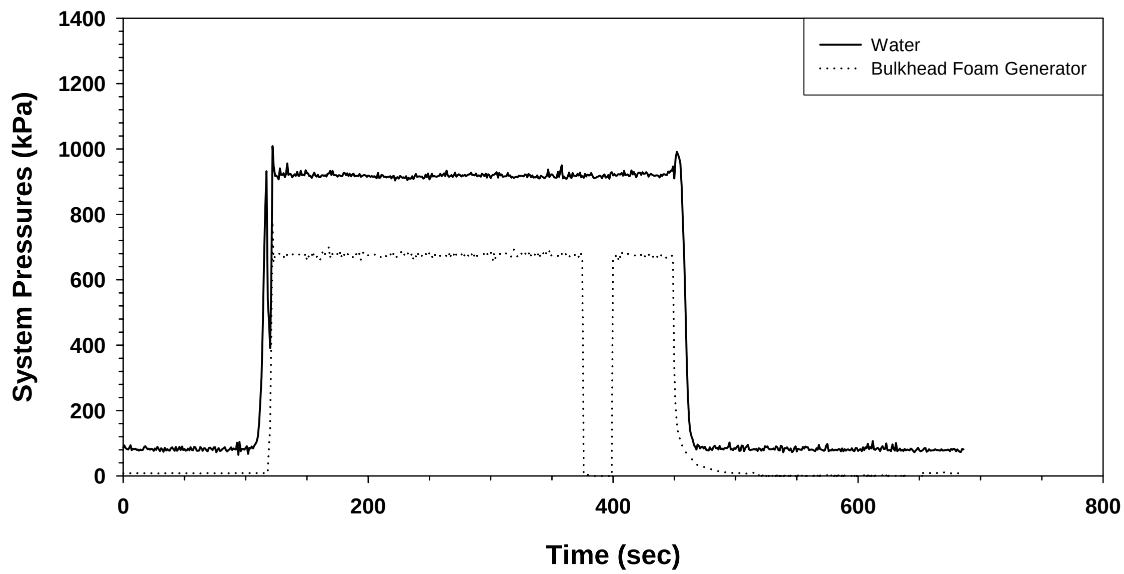
Ansul Test 4 - Heptane Spray on Side



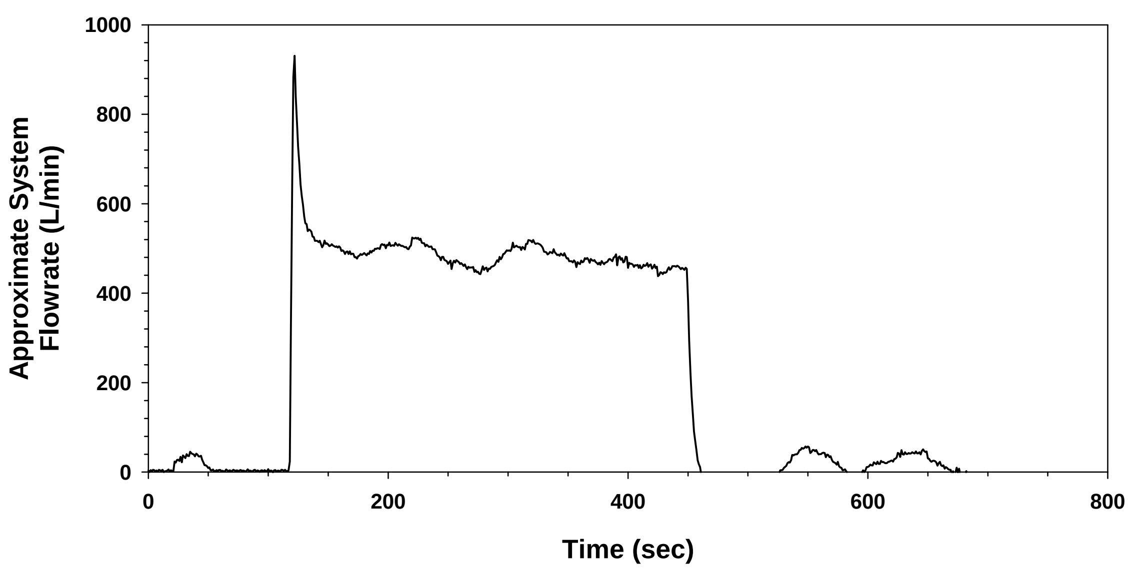
Ansul Test 4 - Heptane Spray on Side



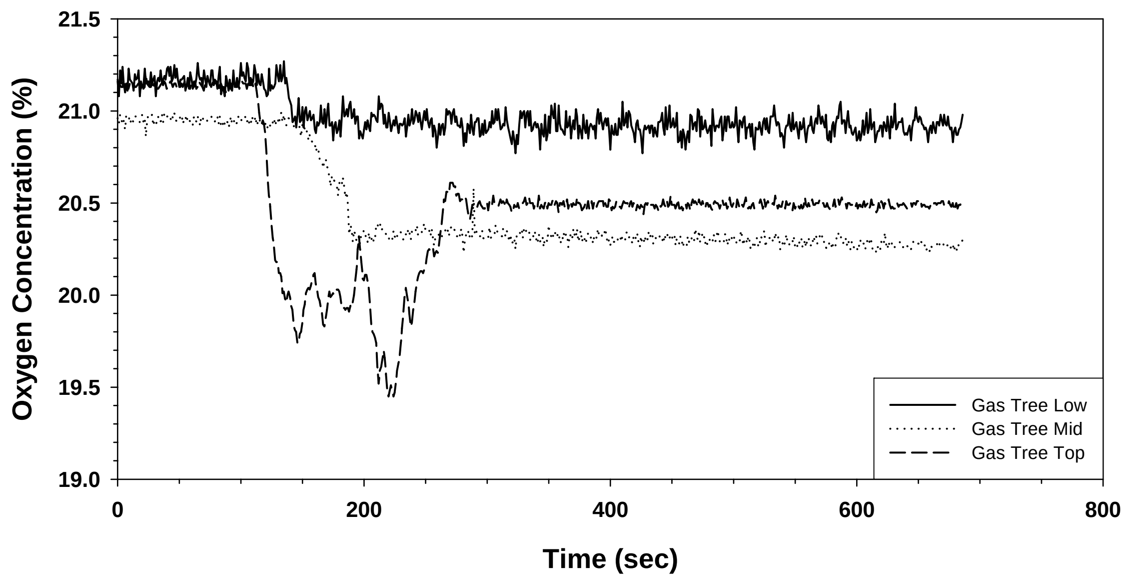
Ansul Test 5 - Heptane Spray on Side



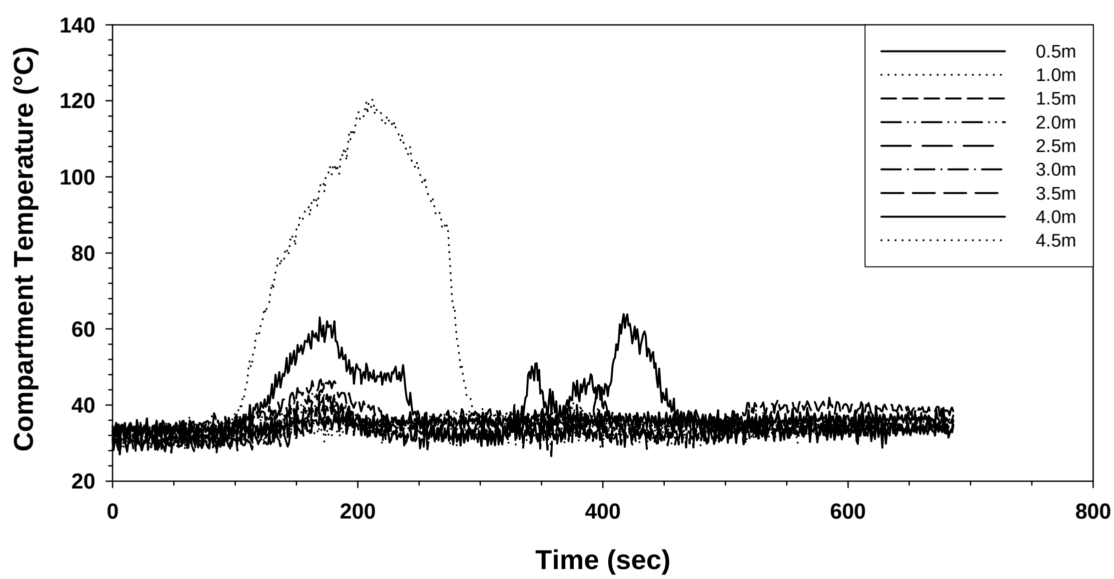
Ansul Test 5 - Heptane Spray on Side



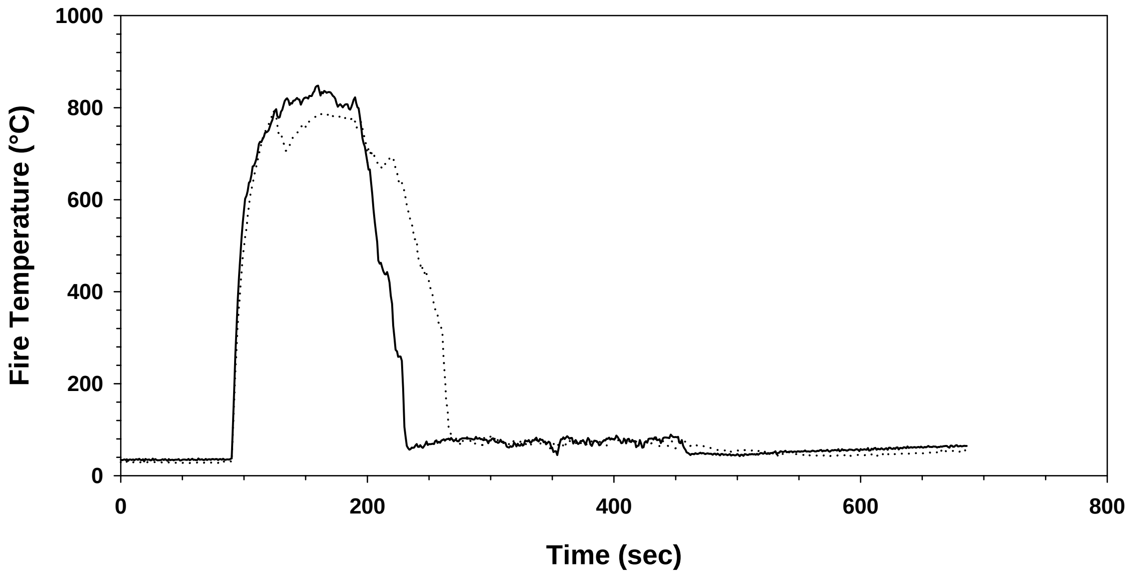
Ansul Test 5 - Heptane Spray on Side



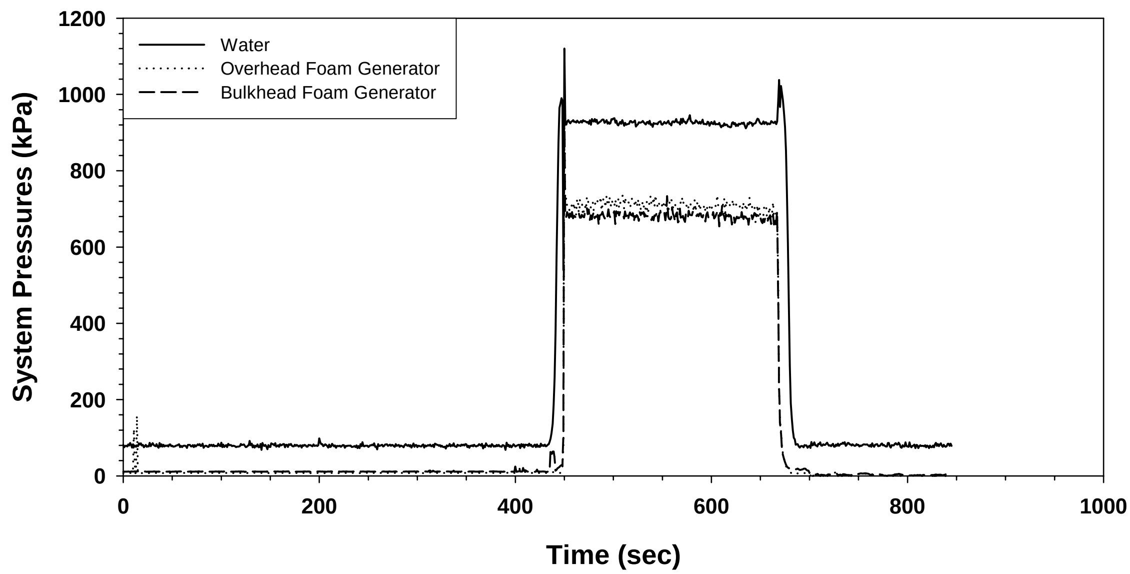
Ansul Test 5 - Heptane Spray on Side



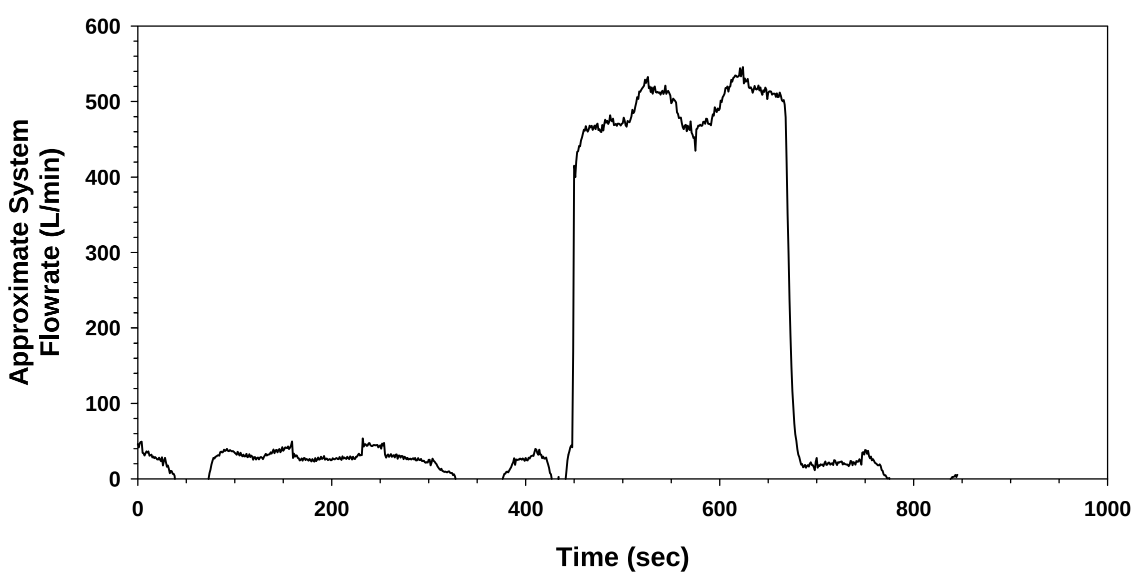
Ansul Test 5 - Heptane Spray on Side

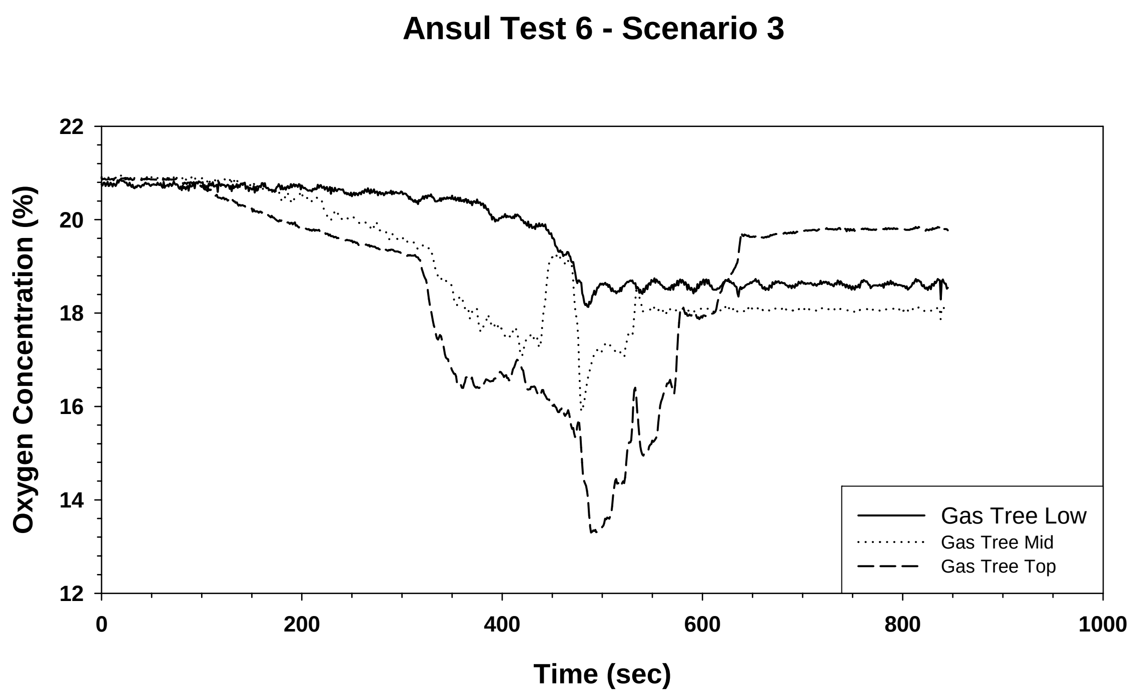


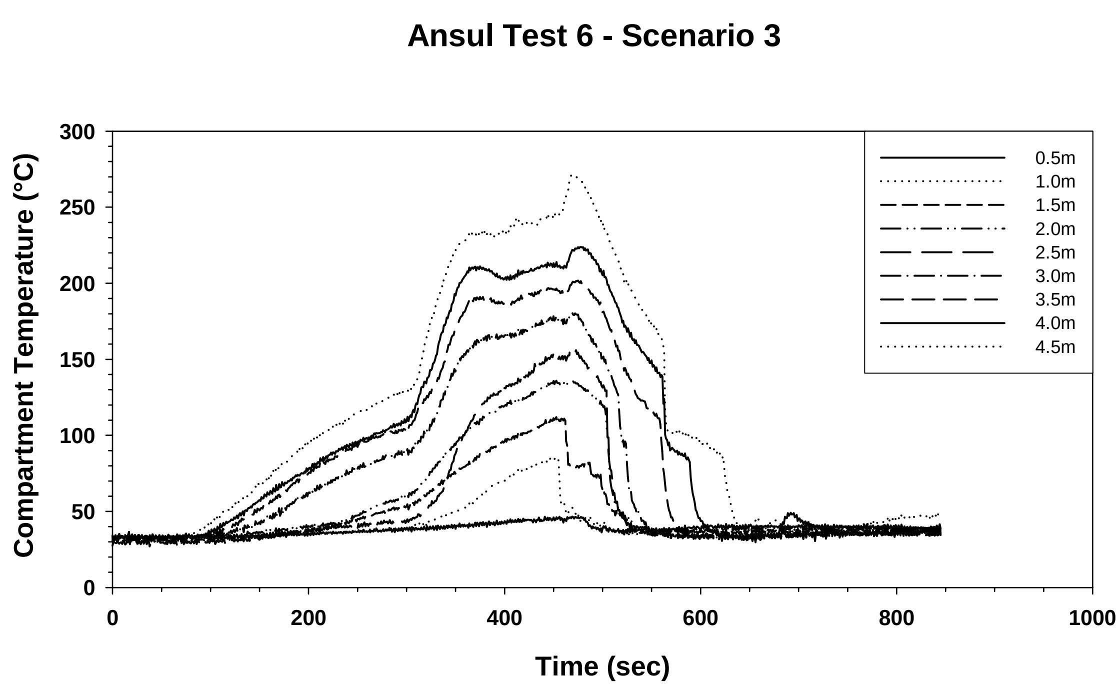
Ansul Test 6 - Scenario 3

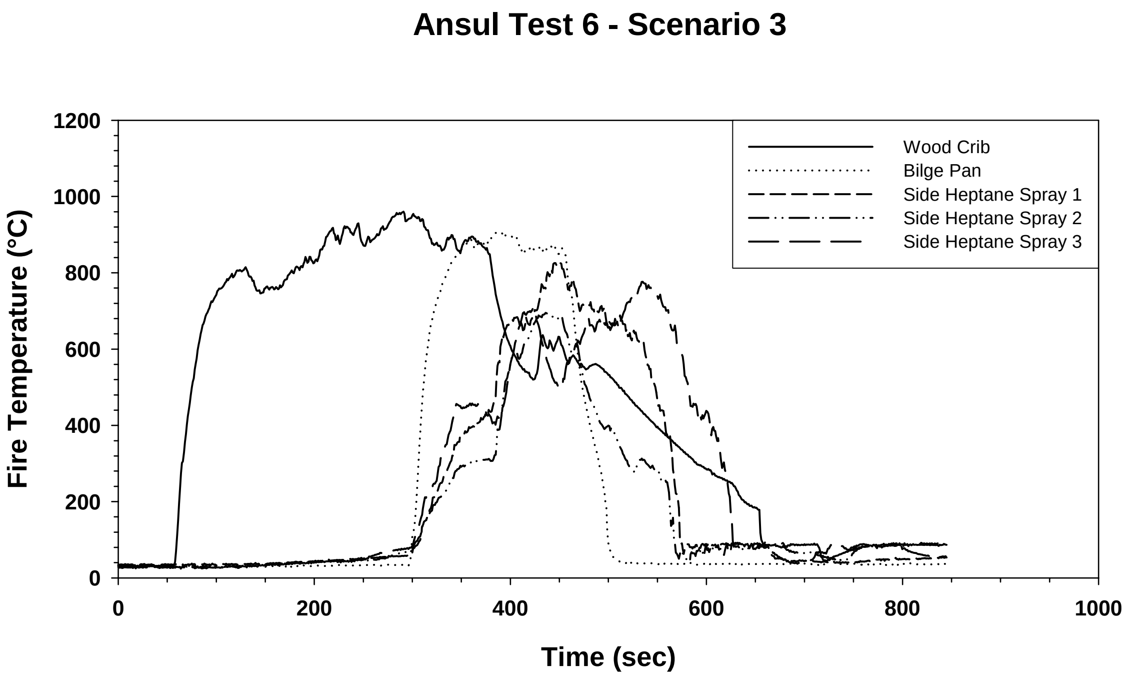


Ansul Test 6 - Scenario 3



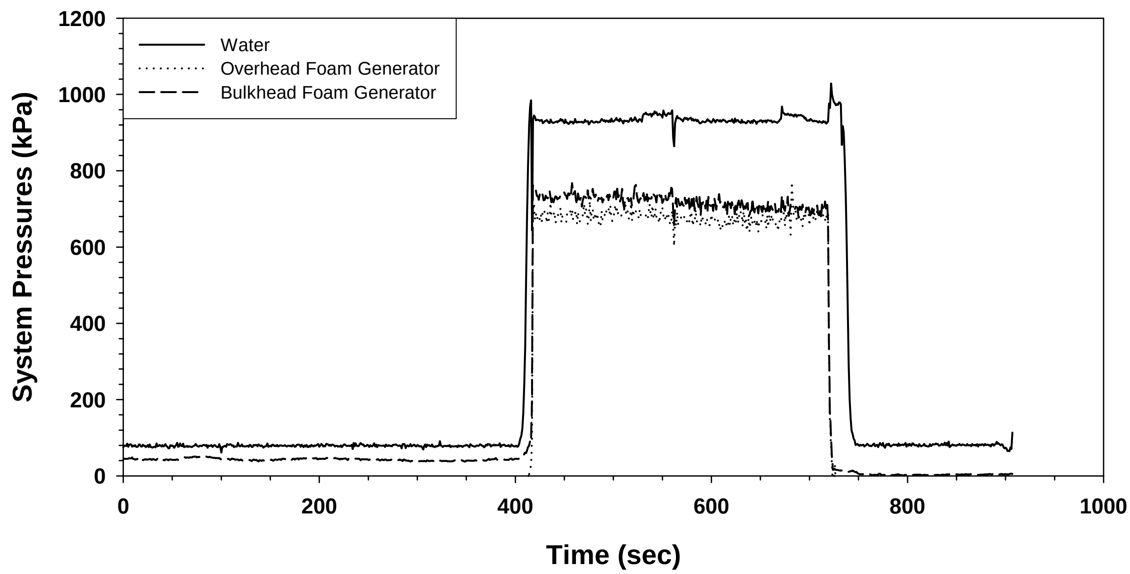

Ansul Test 6 - Scenario 3
Oxygen Concentration (%)
22
20
18
16
14
12
0
200
400
600
800
1000
Time (sec)
Gas Tree Low
Gas Tree Mid
Gas Tree Top


Ansul Test 6 - Scenario 3
Compartment Temperature (°C)
300
250
200
150
100
50
0
0
200
400
600
800
1000
Time (sec)
0.5m
1.0m
1.5m
2.0m
2.5m
3.0m
3.5m
4.0m
4.5m

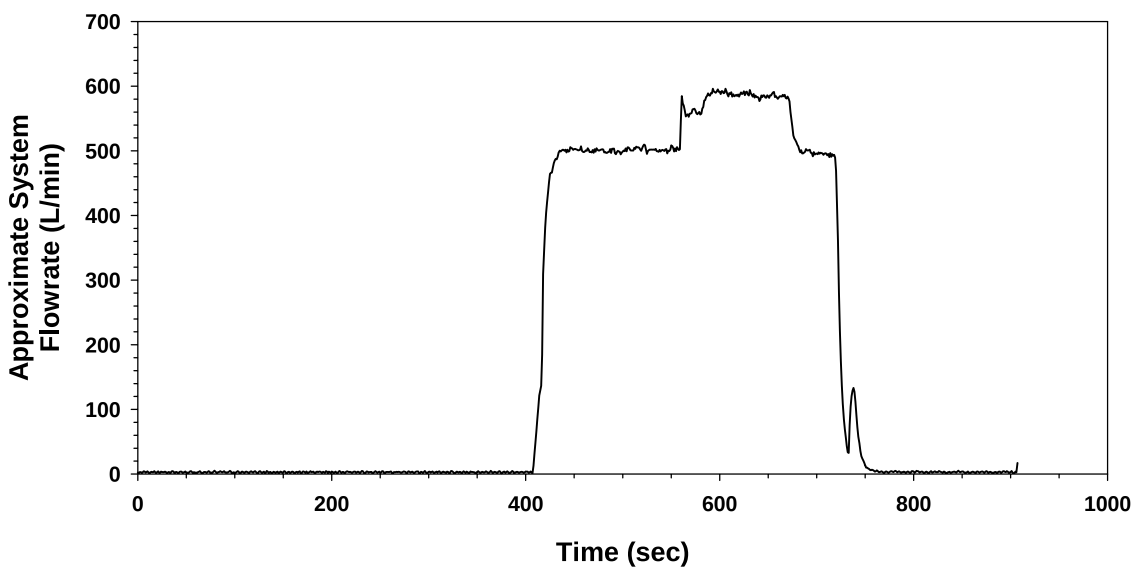


Ansul Test 6 - Scenario 3
Fire Temperature (°C)
Time (sec)
0
200
400
600
800
1000
1200
Wood Crib
Bilge Pan
Side Heptane Spray 1
Side Heptane Spray 2
Side Heptane Spray 3

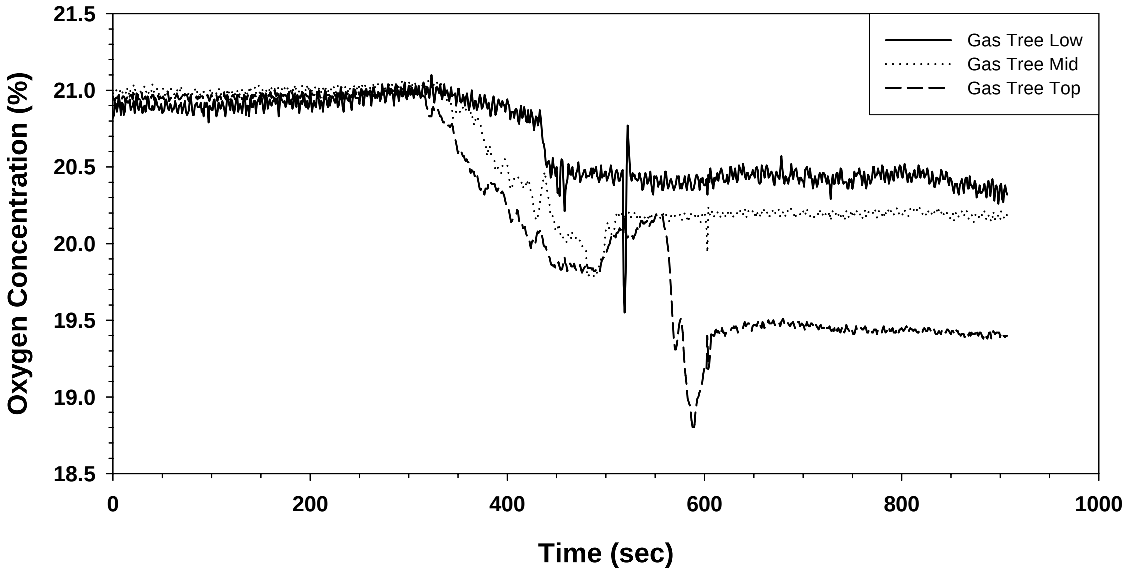
Ansul Test 7 - Scenario 2



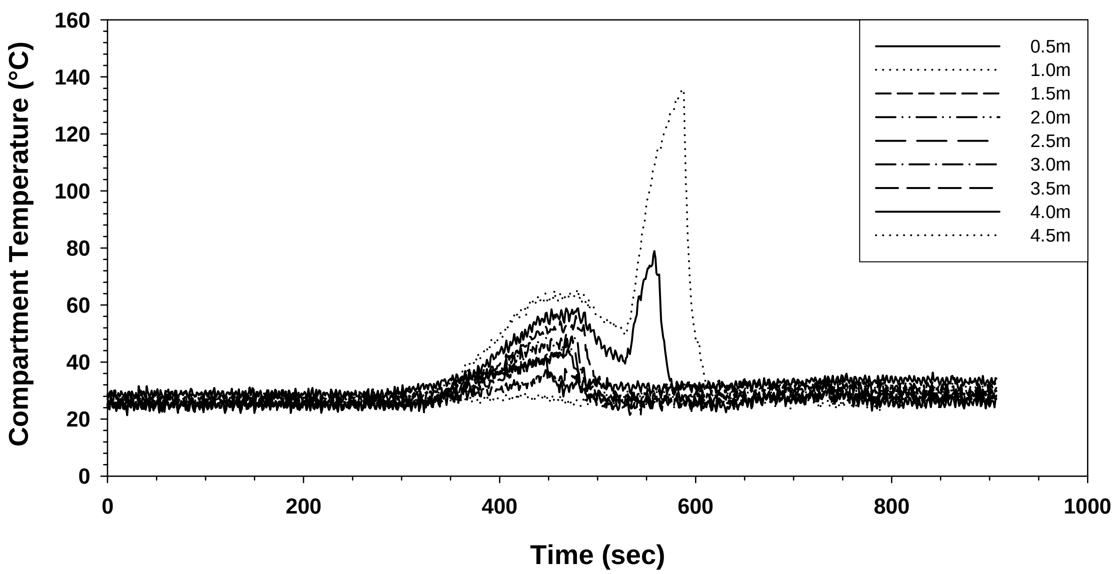
Ansul Test 7 - Scenario 2

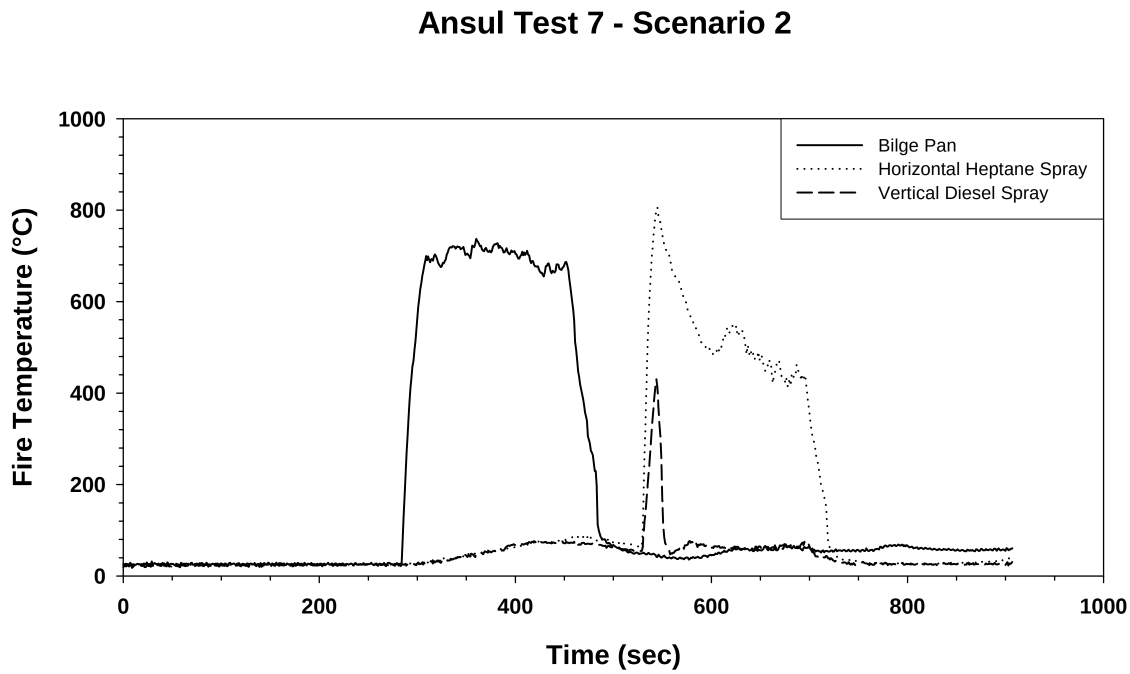


Ansul Test 7 - Scenario 2



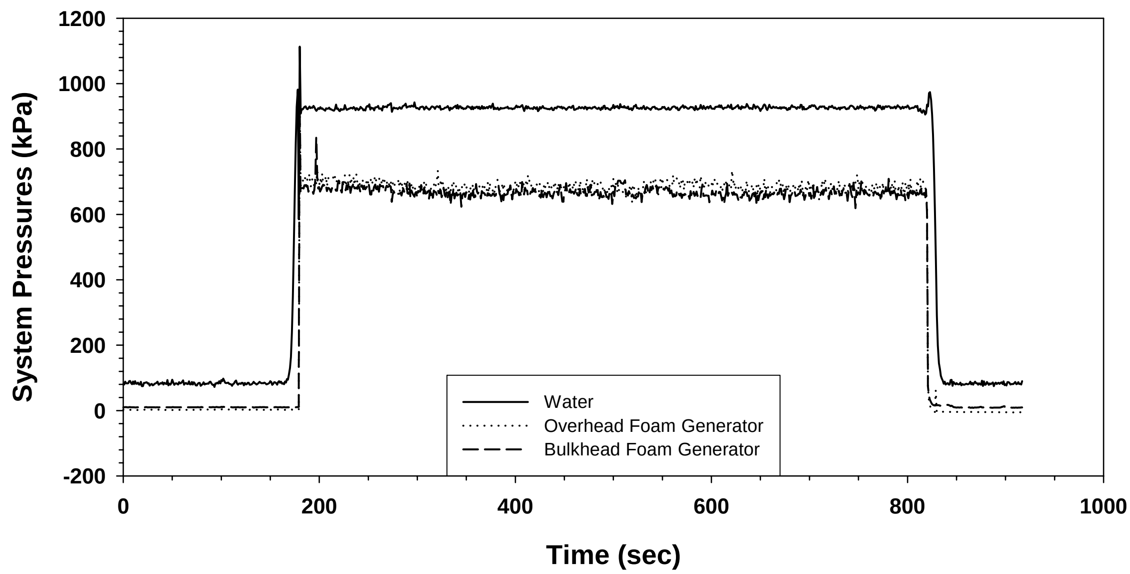
Ansul Test 7 - Scenario 2



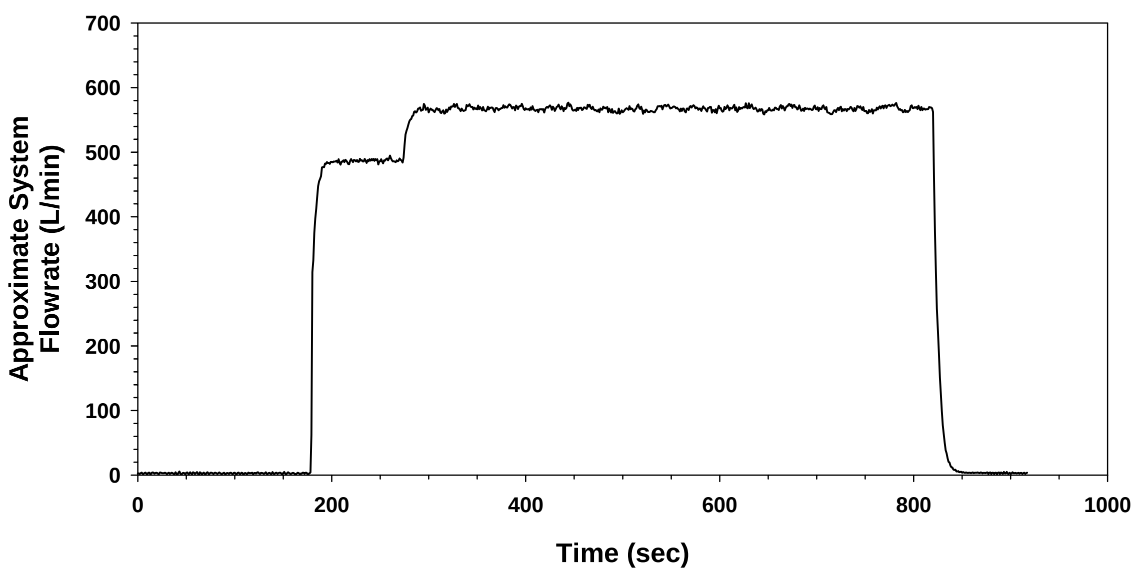


Ansul Test 7 - Scenario 2
Bilge Pan
Horizontal Heptane Spray
Vertical Diesel Spray
Fire Temperature (°C)
Time (sec)
0
200
400
600
800
1000
0
200
400
600
800
1000

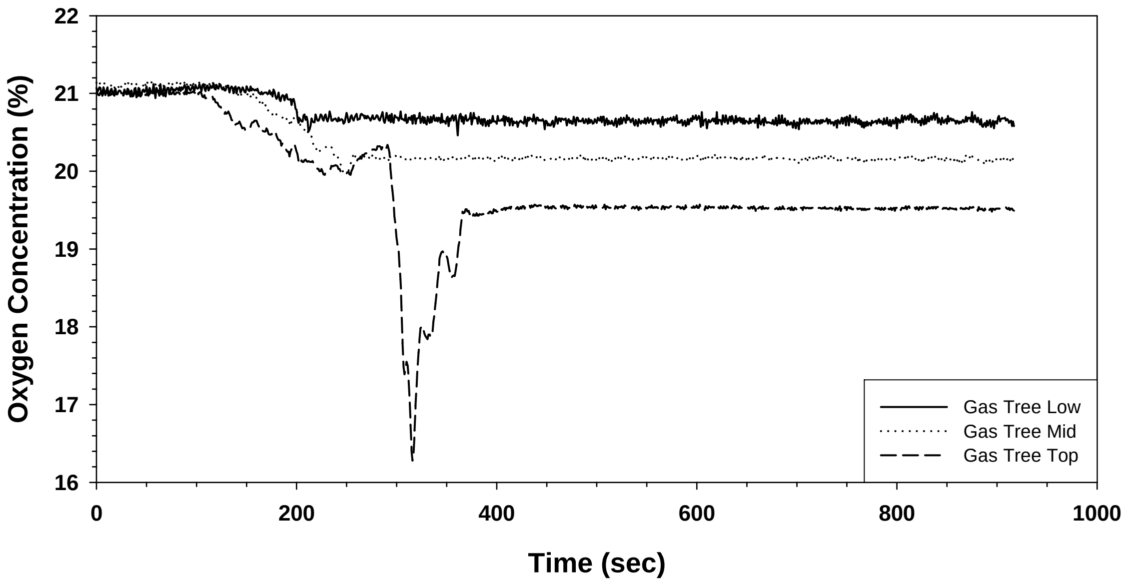
Ansul Test 8 - Scenario 2



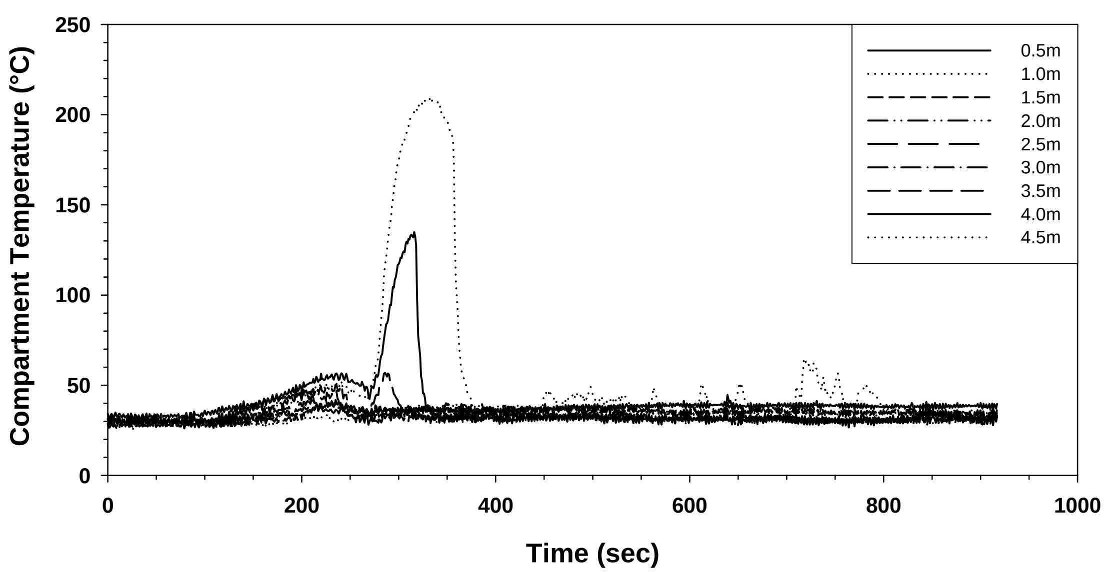
Ansul Test 8 - Scenario 2

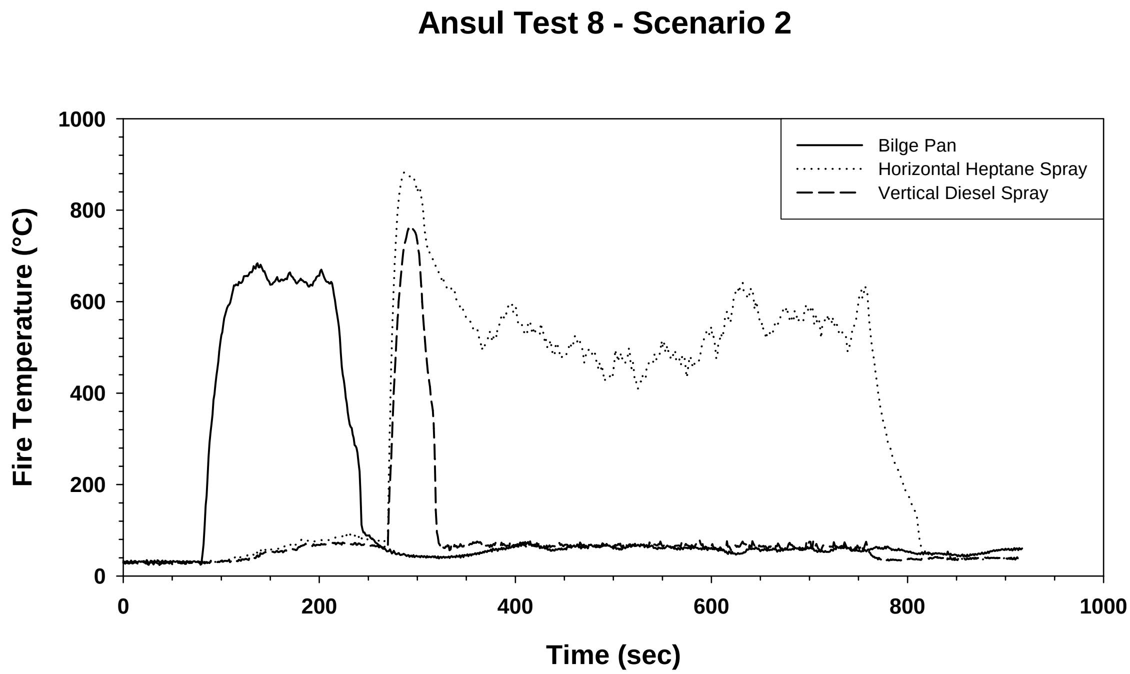


Ansul Test 8 - Scenario 2

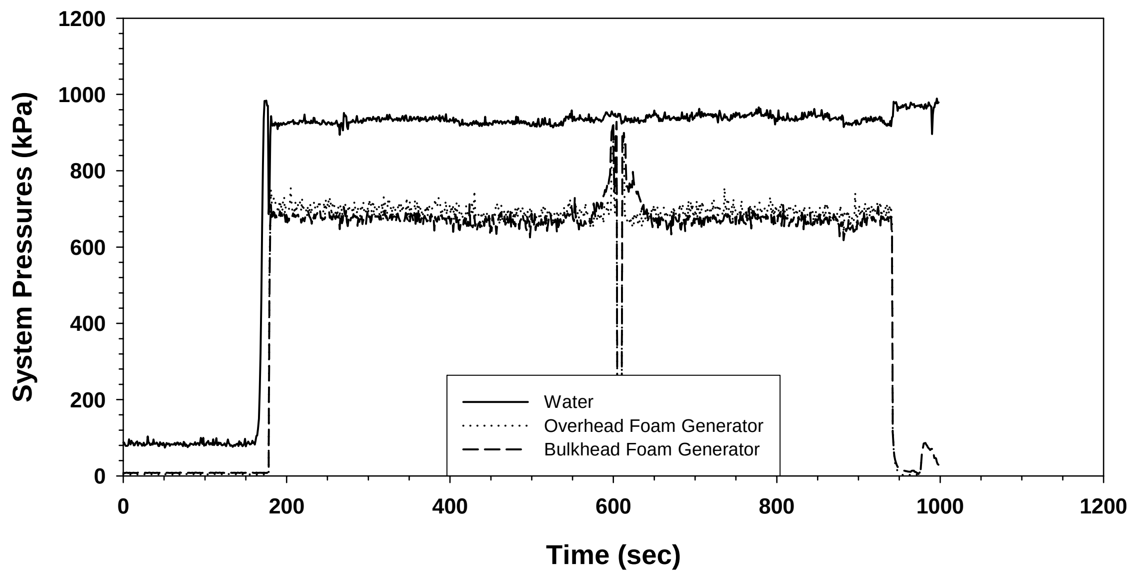


Ansul Test 8 - Scenario 2

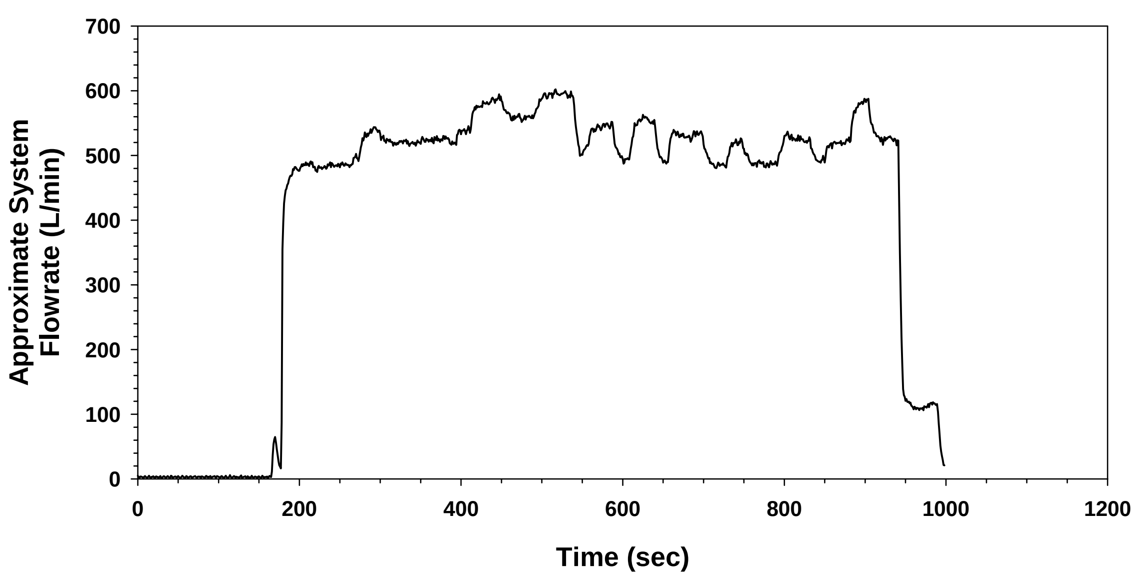



Ansul Test 8 - Scenario 2
Bilge Pan
Horizontal Heptane Spray
Vertical Diesel Spray
Fire Temperature (°C)
Time (sec)
0
200
400
600
800
1000
0
200
400
600
800
1000

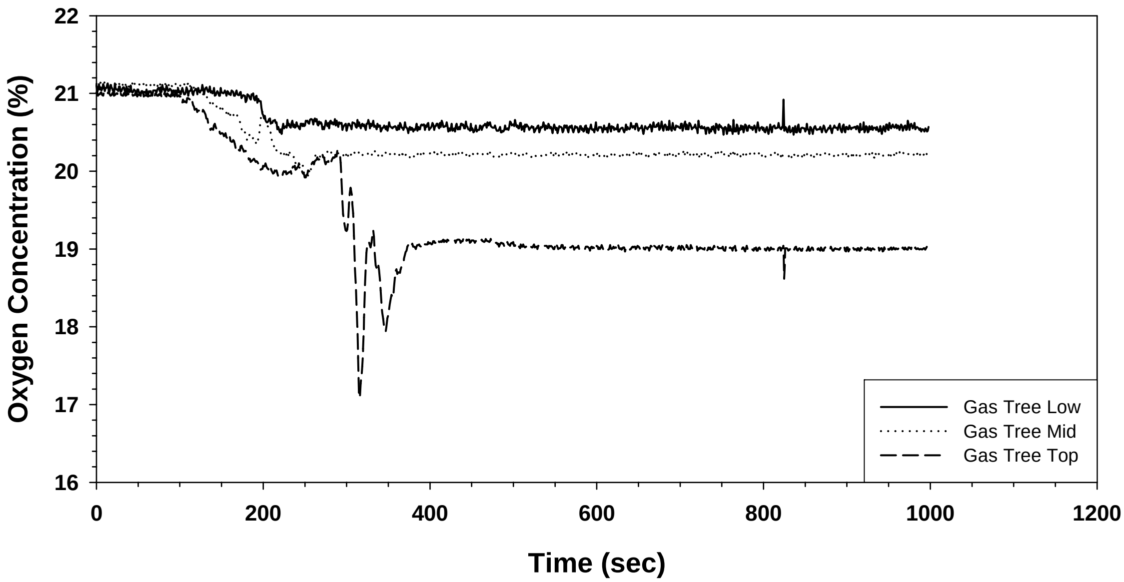
Ansul Test 9 - Scenario 2



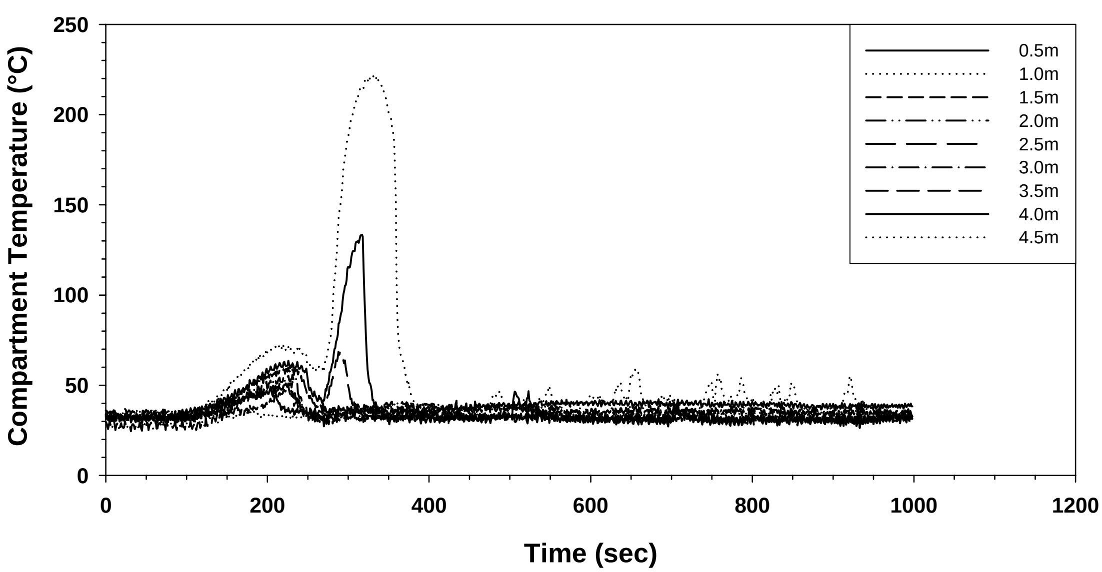
Ansul Test 9 - Scenario 2



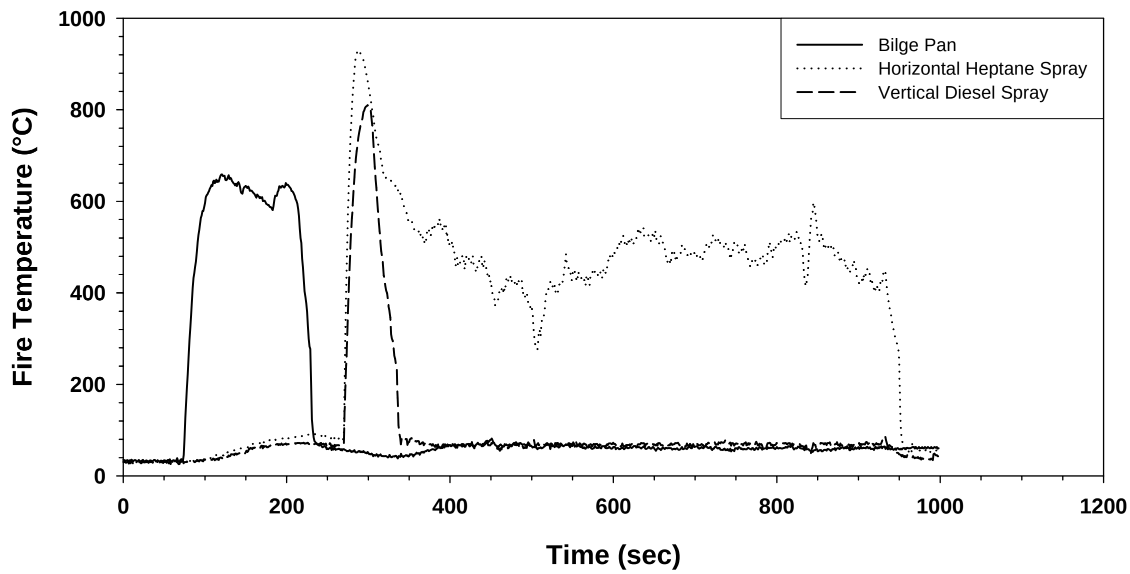
Ansul Test 9 - Scenario 2



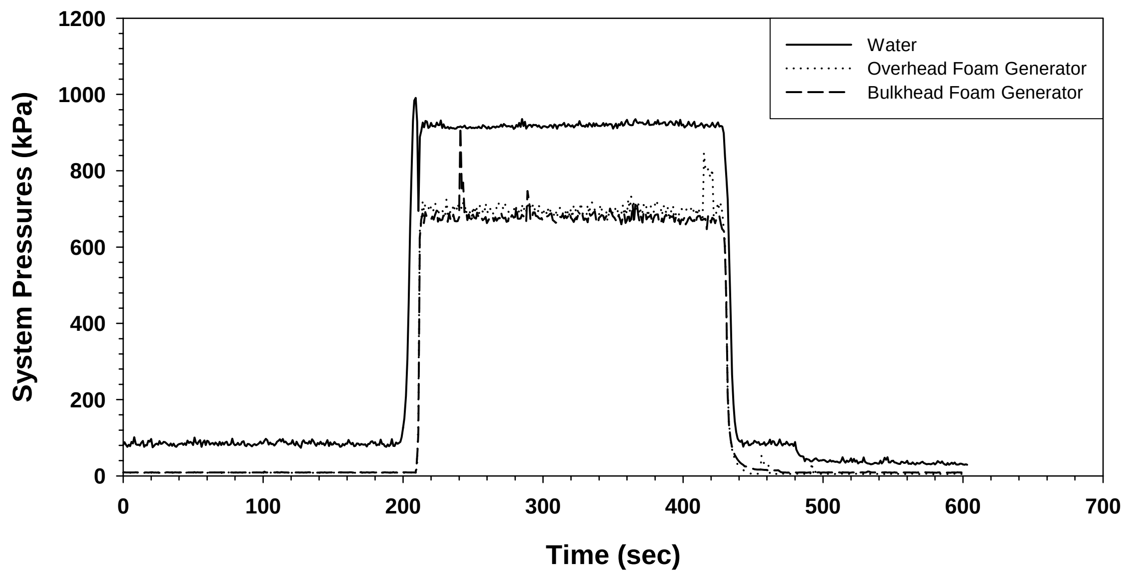
Ansul Test 9 - Scenario 2



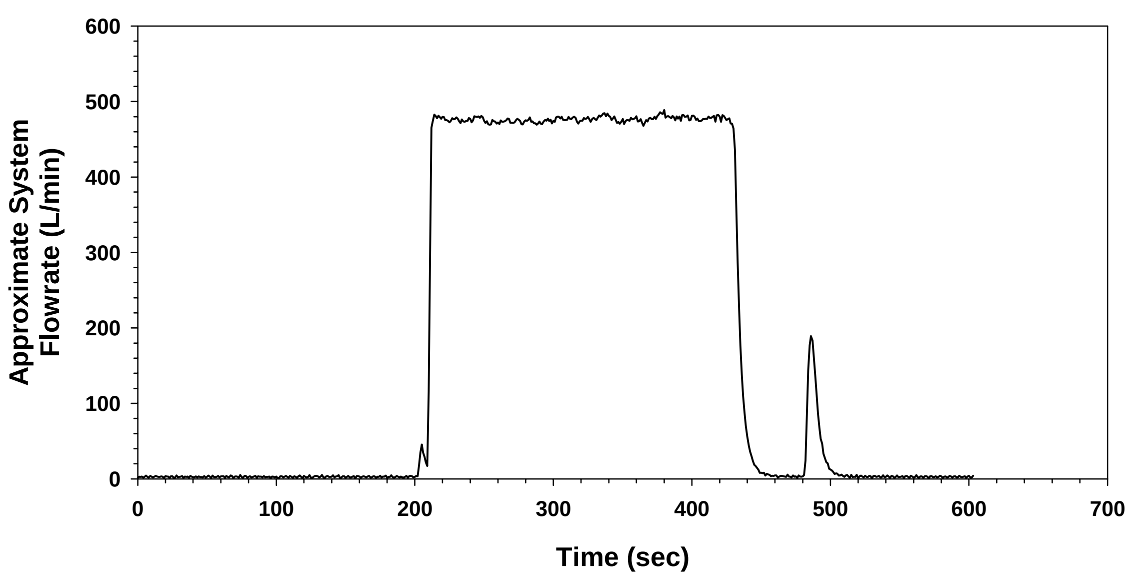
Ansul Test 9 - Scenario 2

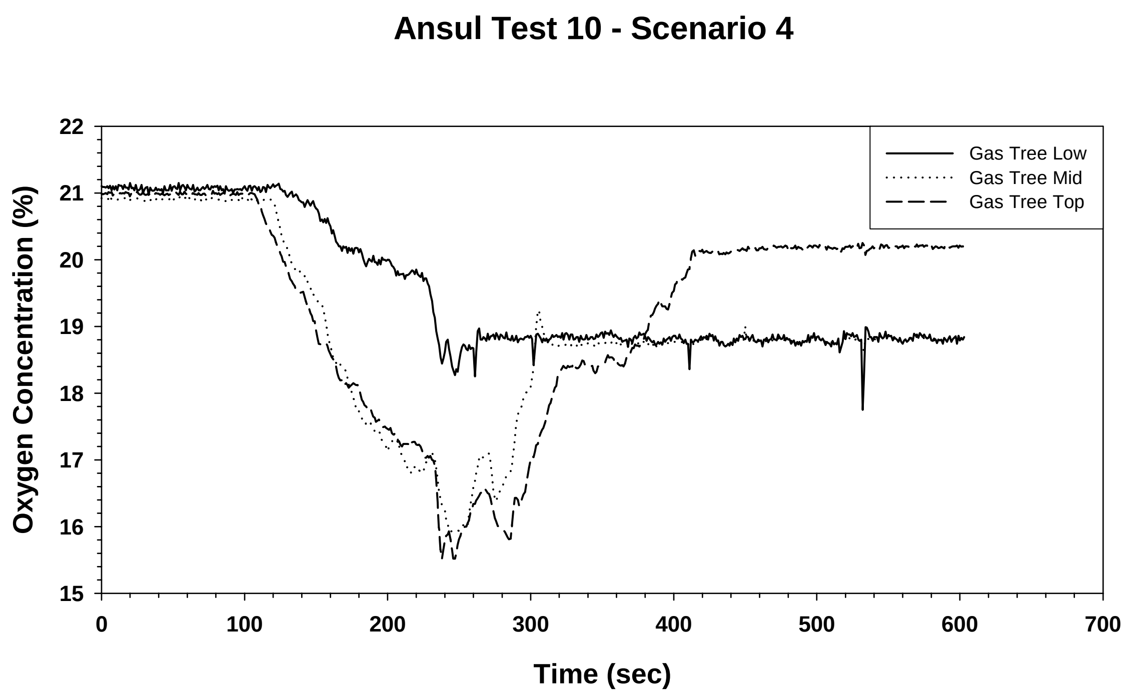


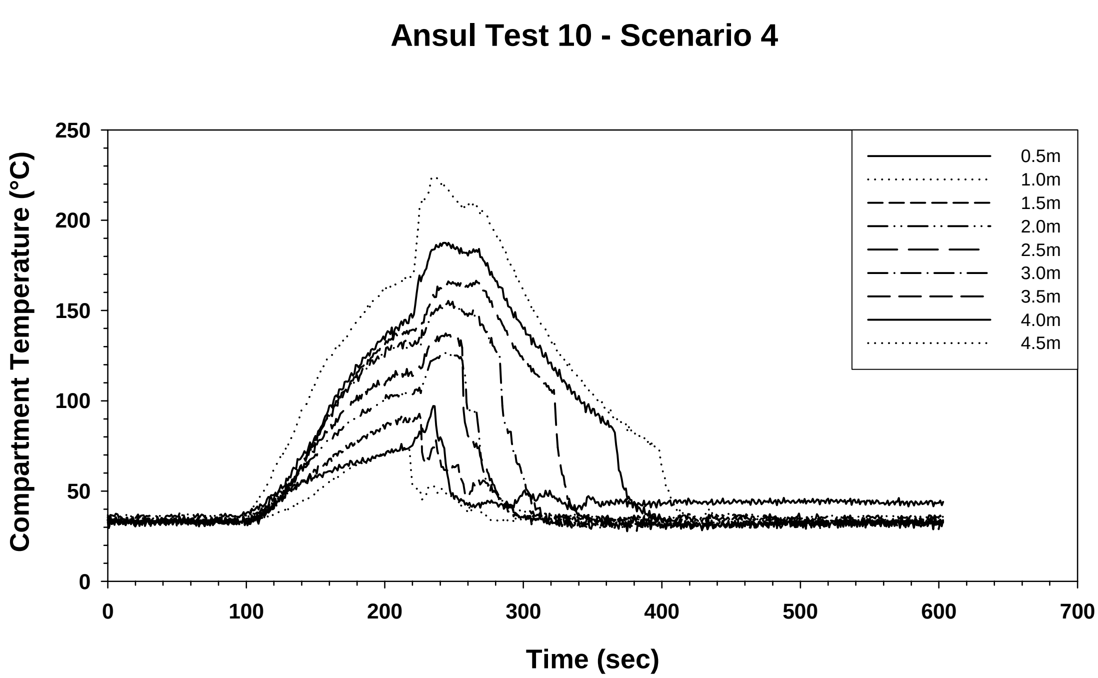
Ansul Test 10 - Scenario 4



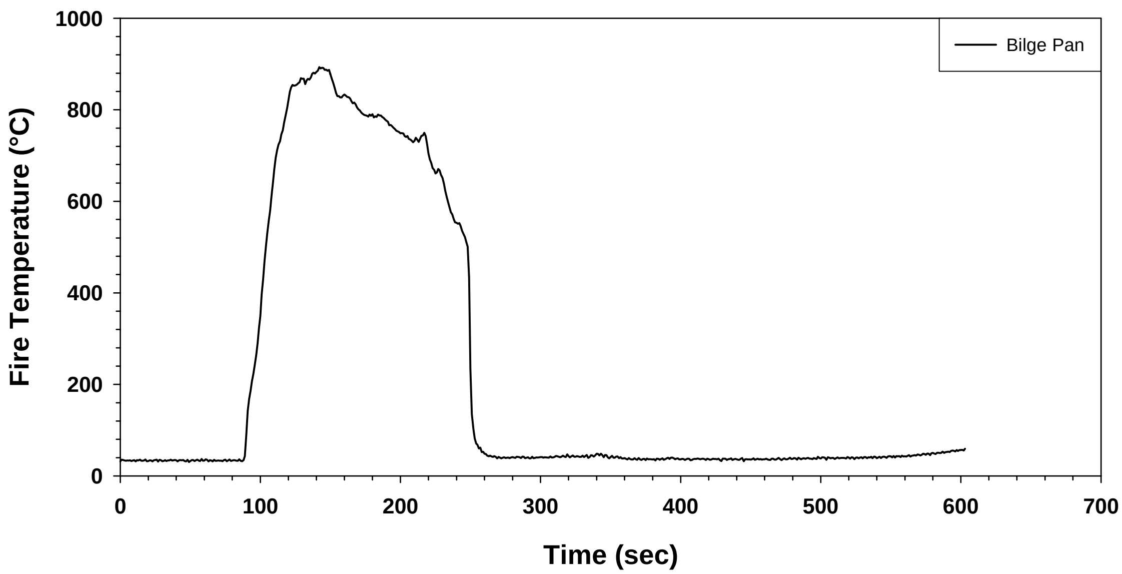
Ansul Test 10 - Scenario 4



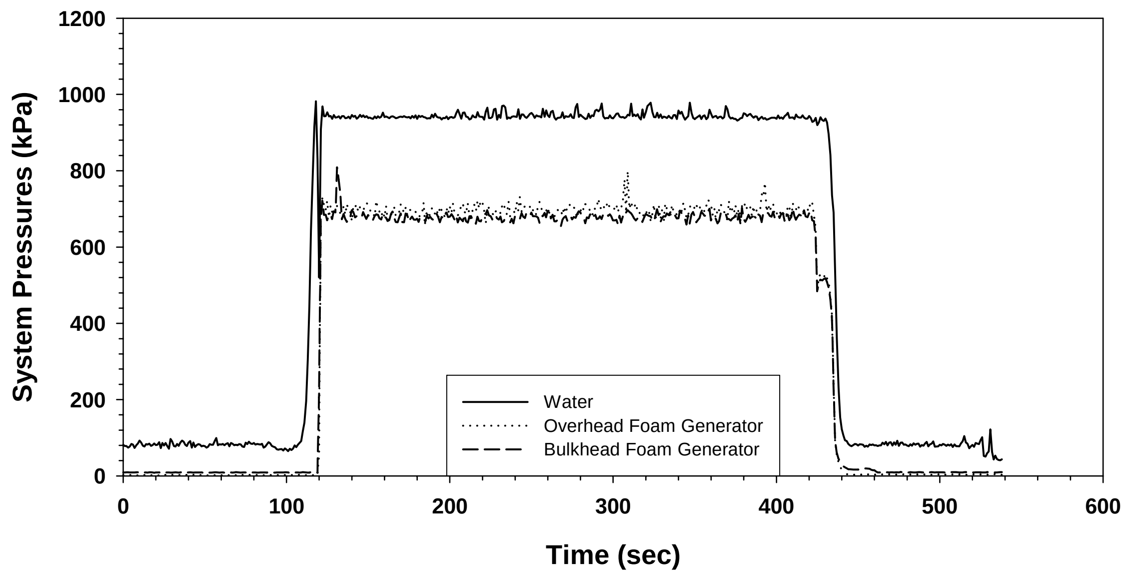

Ansul Test 10 - Scenario 4
Oxygen Concentration (%)
Time (sec)
Gas Tree Low
Gas Tree Mid
Gas Tree Top
22
21
20
19
18
17
16
15
0
100
200
300
400
500
600
700


Ansul Test 10 - Scenario 4
Compartment Temperature (°C)
Time (sec)
0.5m
1.0m
1.5m
2.0m
2.5m
3.0m
3.5m
4.0m
4.5m
250
200
150
100
50
0
0
100
200
300
400
500
600
700

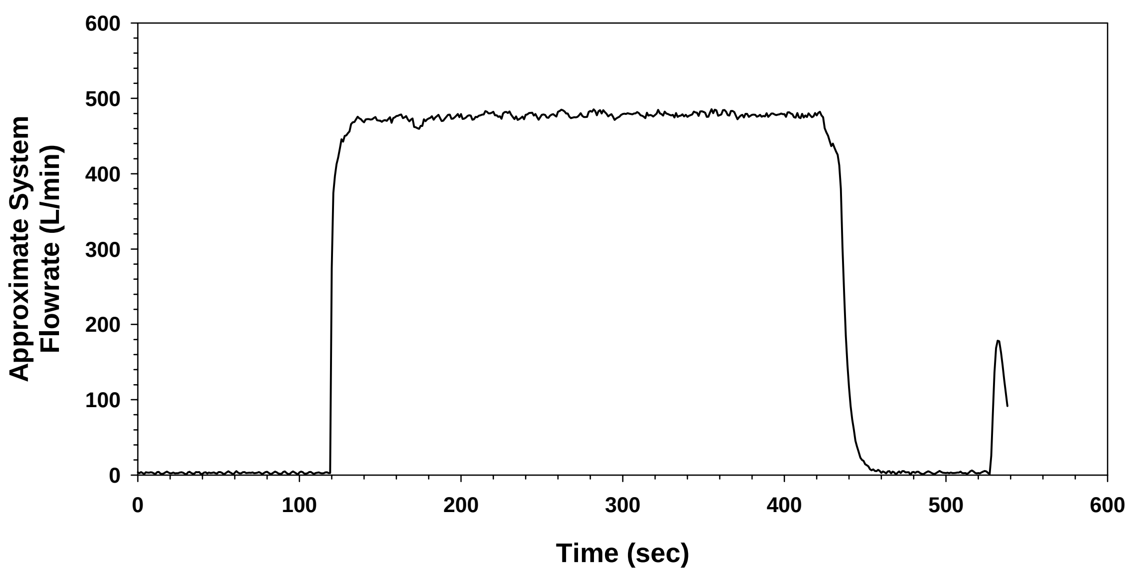
Ansul Test 10 - Scenario 4

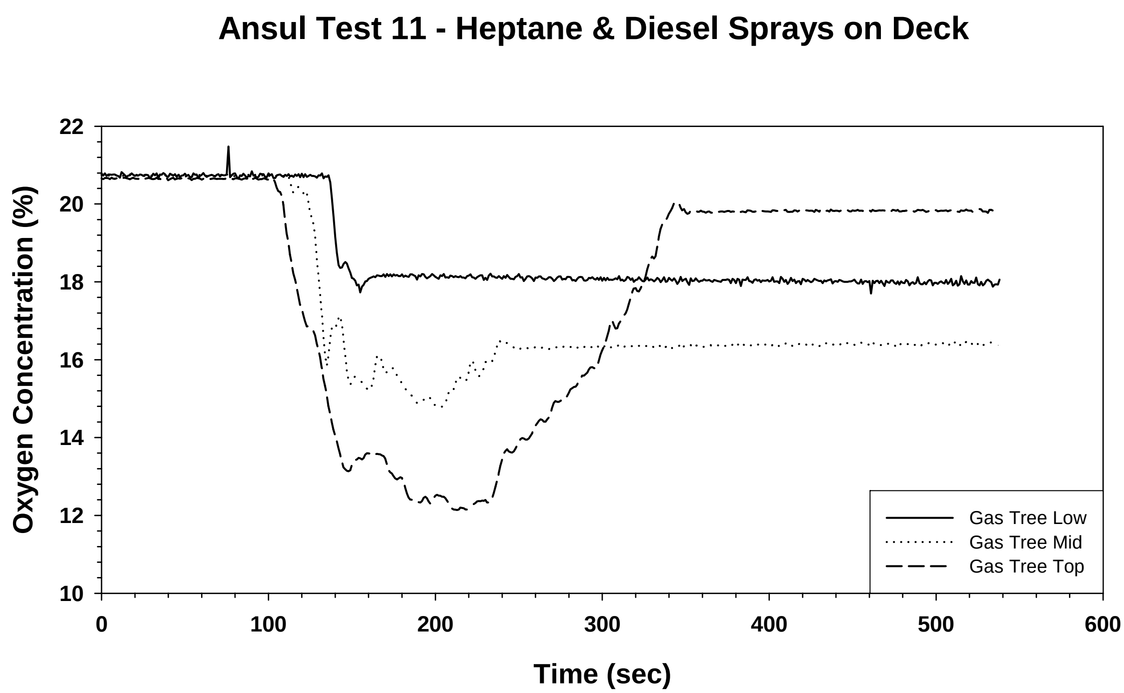


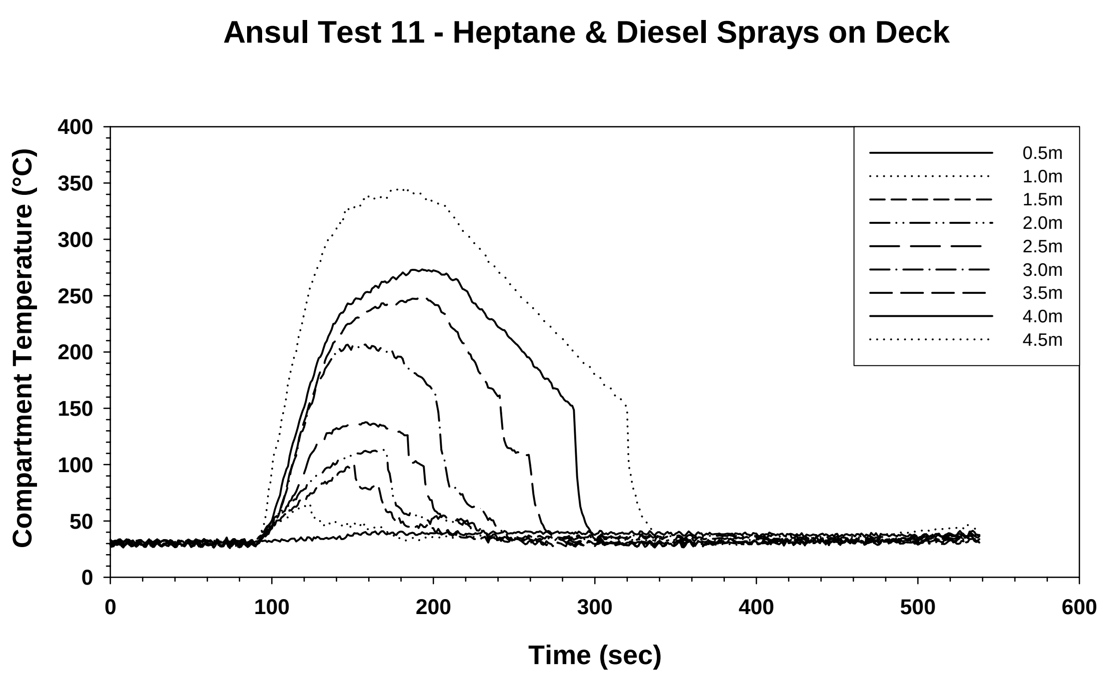
Ansul Test 11 - Heptane & Diesel Sprays on Deck



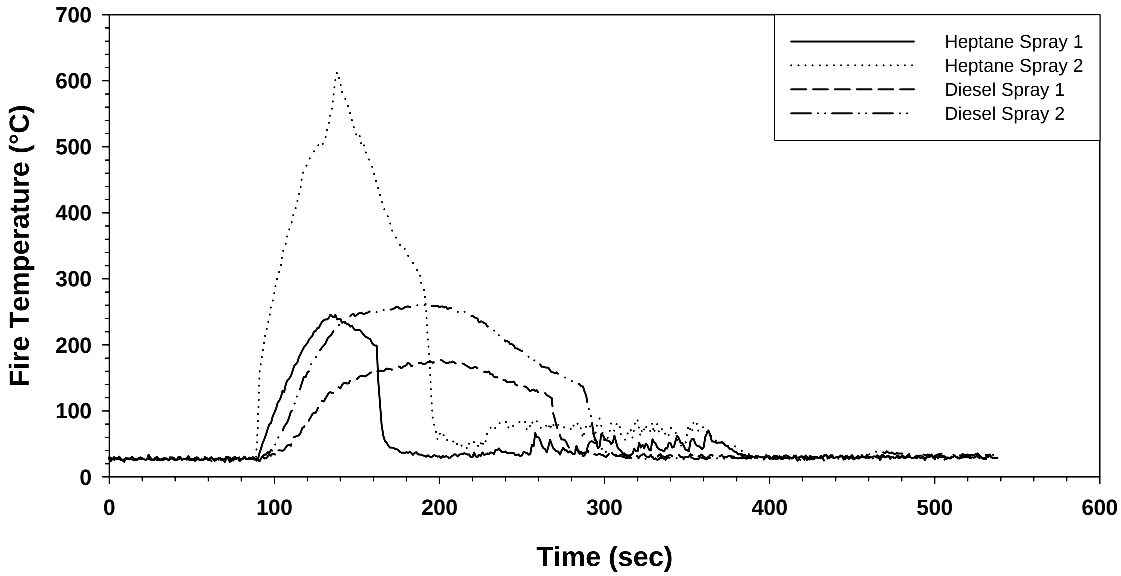
Ansul Test 11 - Heptane & Diesel Sprays on Deck



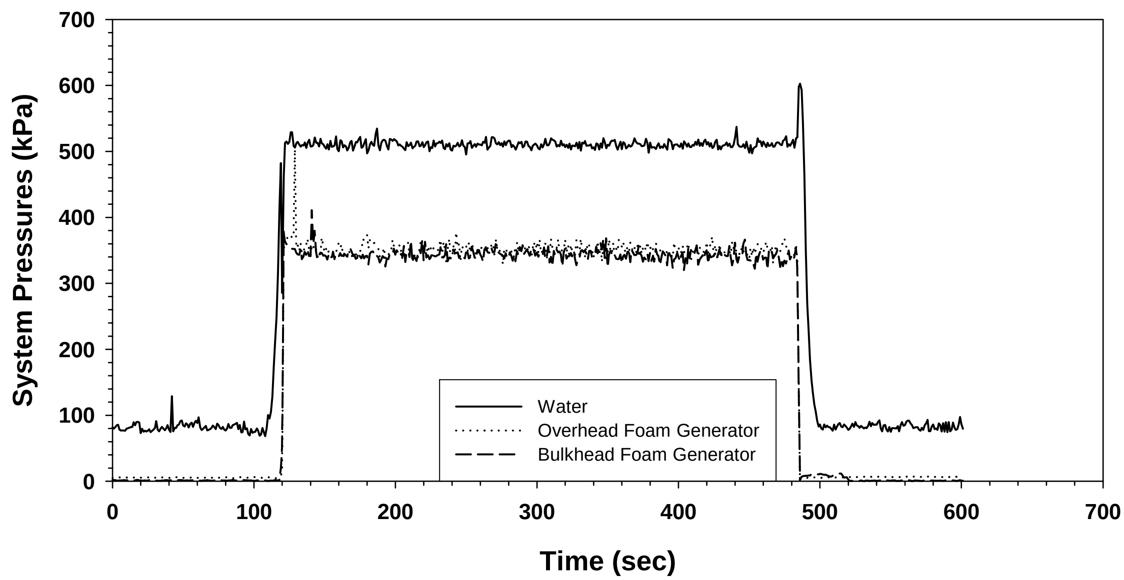

Ansul Test 11 - Heptane & Diesel Sprays on Deck
Oxygen Concentration (%)
22
20
18
16
14
12
10
0
100
200
300
400
500
600
Time (sec)
Gas Tree Low
Gas Tree Mid
Gas Tree Top


Ansul Test 11 - Heptane & Diesel Sprays on Deck
Compartment Temperature (°C)
400
350
300
250
200
150
100
50
0
0
100
200
300
400
500
600
Time (sec)
0.5m
1.0m
1.5m
2.0m
2.5m
3.0m
3.5m
4.0m
4.5m

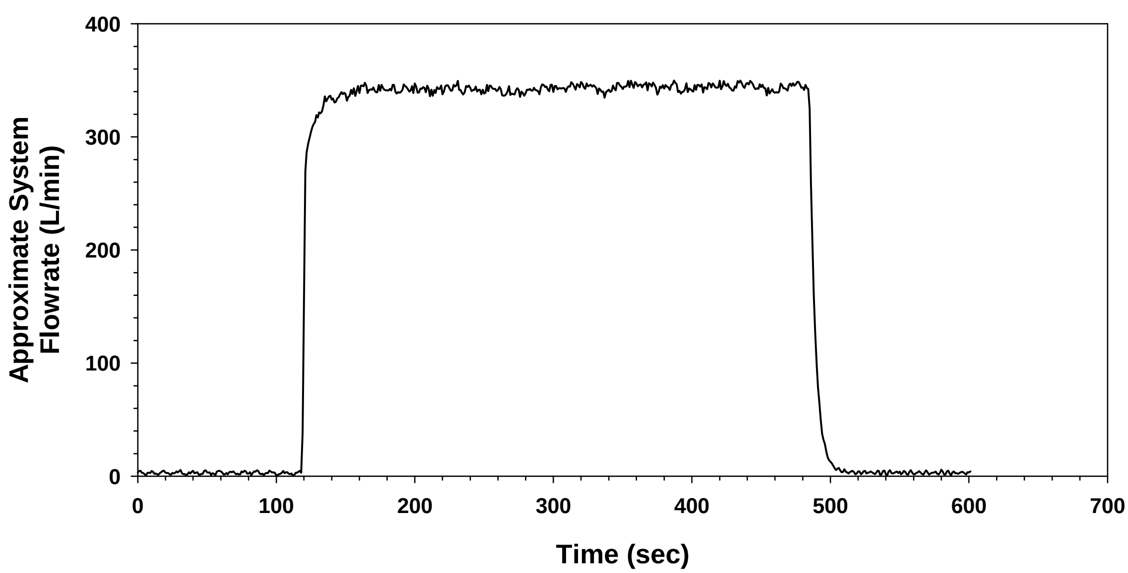
Ansul Test 11 - Heptane & Diesel Sprays on Deck



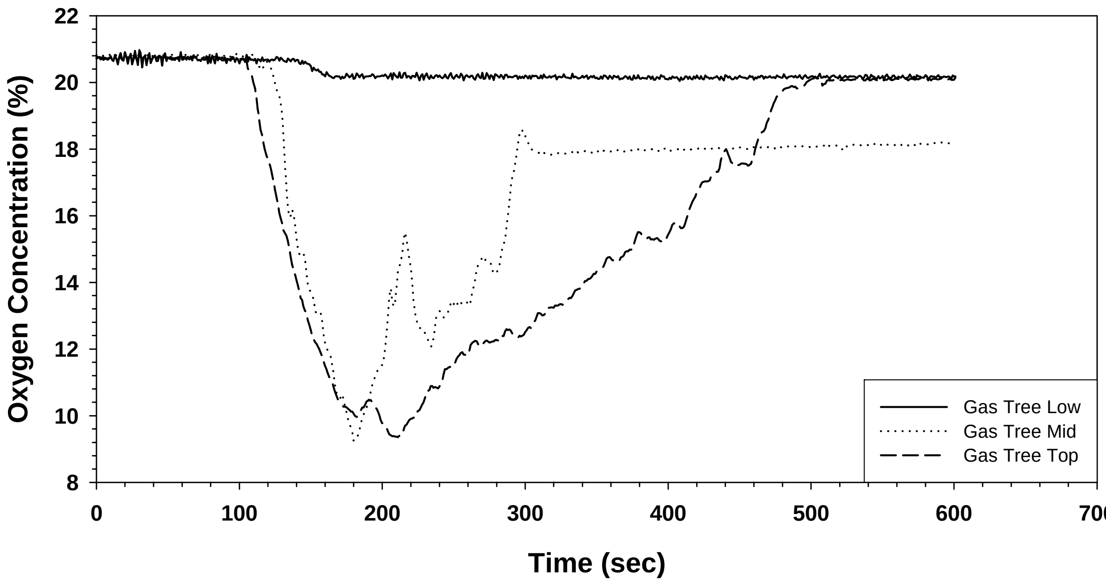
Ansul Test 12 - Heptane & Diesel Sprays on Deck



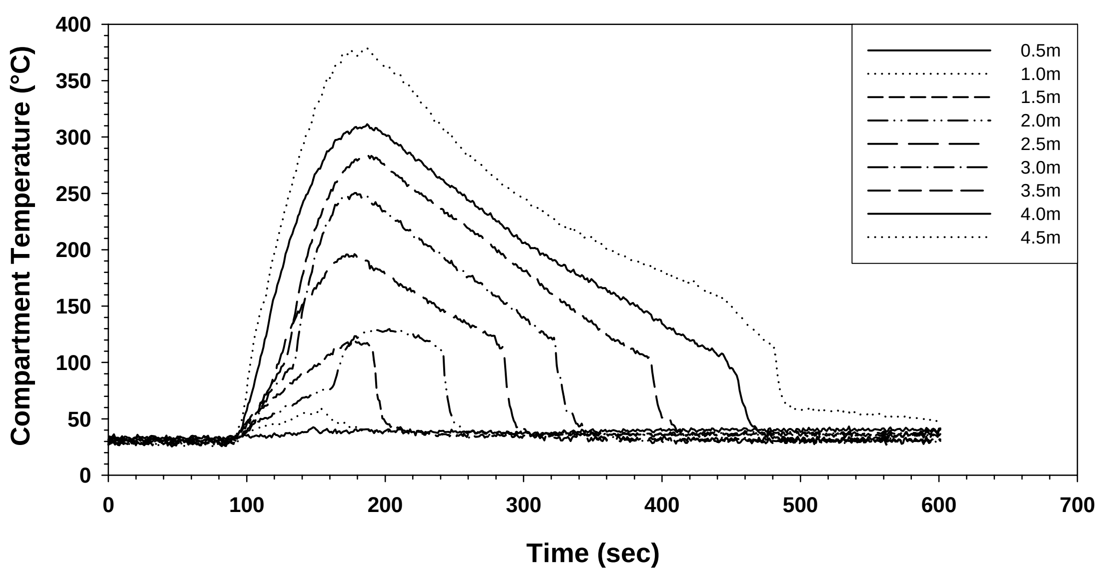
Ansul Test 12 - Heptane & Diesel Sprays on Deck



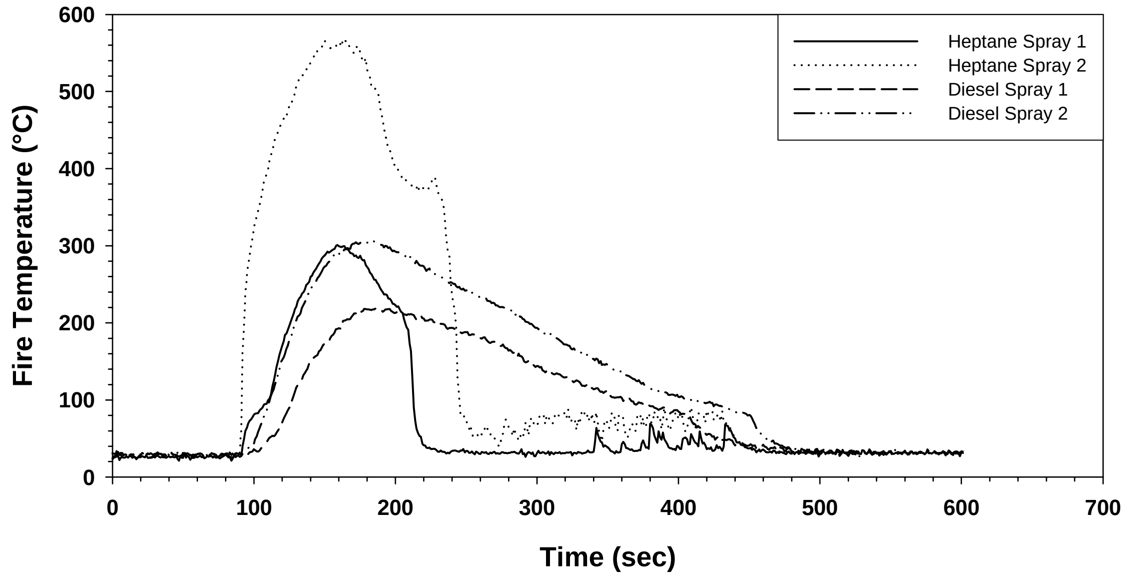
Ansul Test 12 - Heptane & Diesel Sprays on Deck



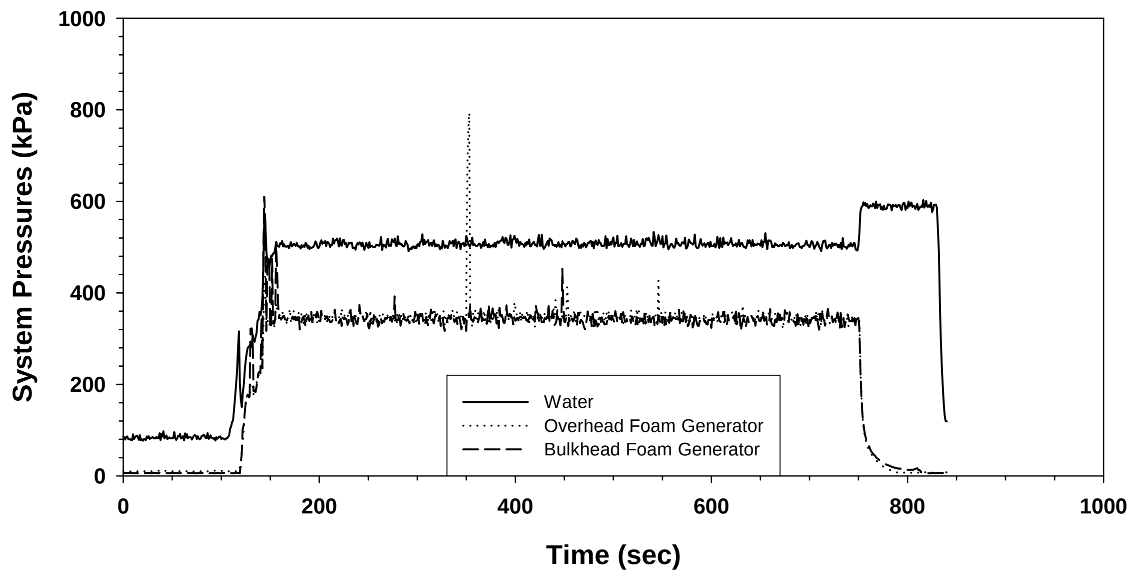
Ansul Test 12 - Heptane & Diesel Sprays on Deck



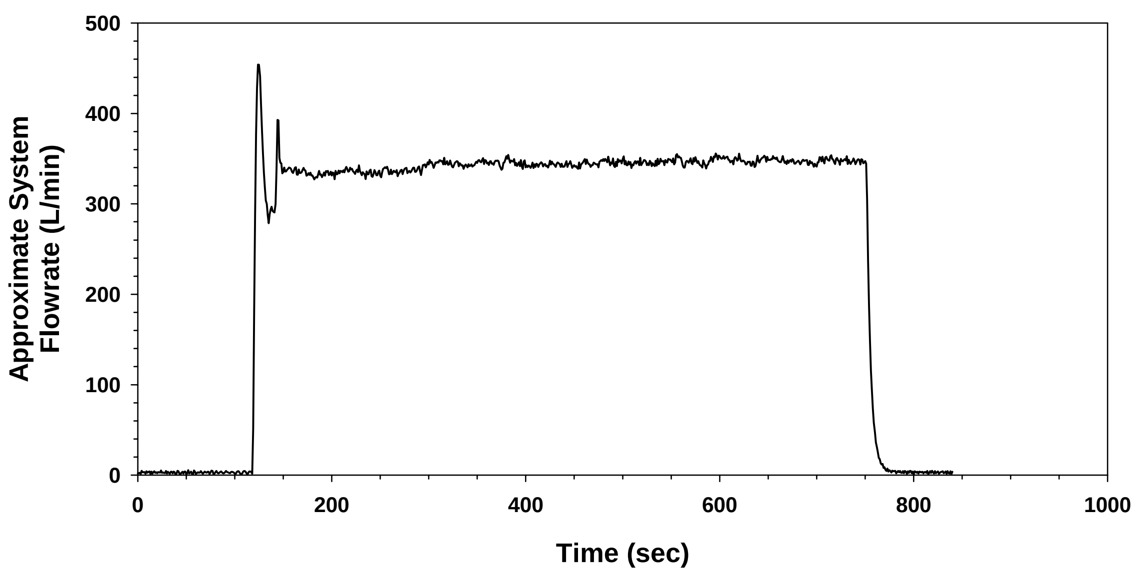
Ansul Test 12 - Heptane & Diesel Sprays on Deck



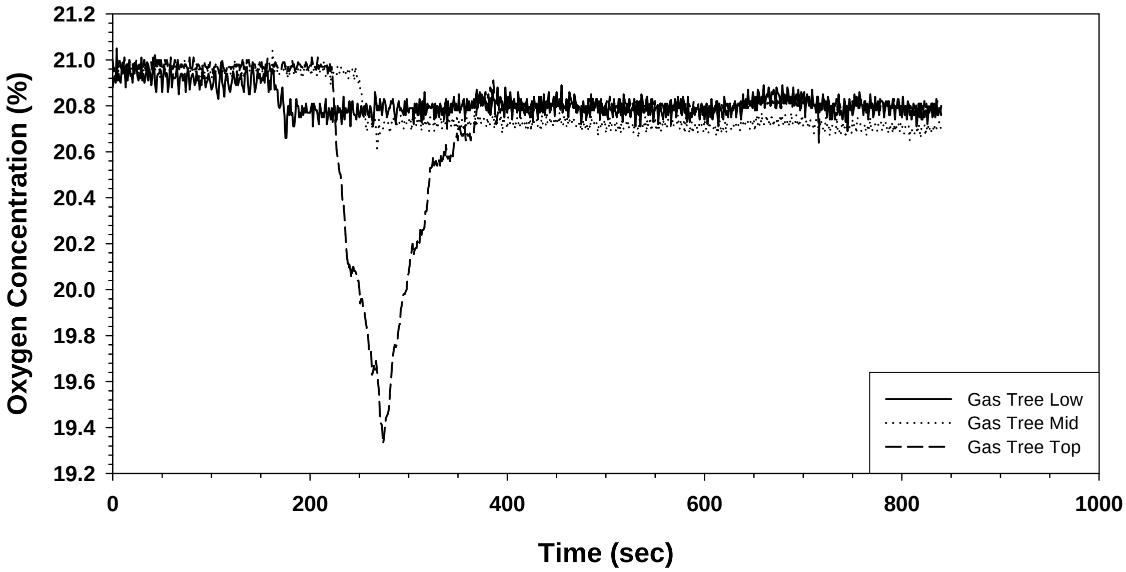
Ansul Test 13 - Heptane Spray on Side



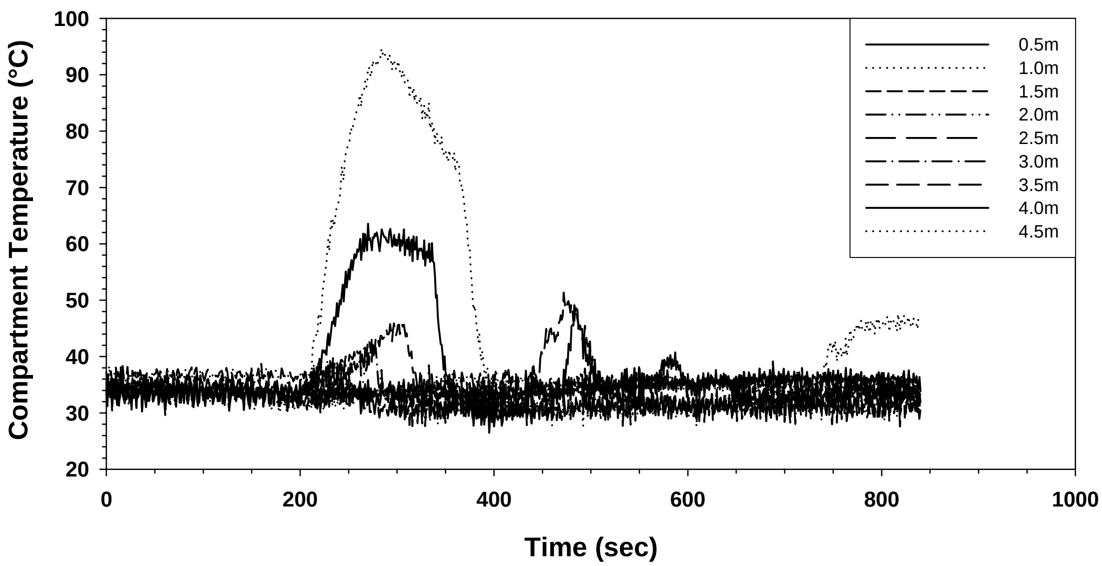
Ansul Test 13 - Heptane Spray on Side



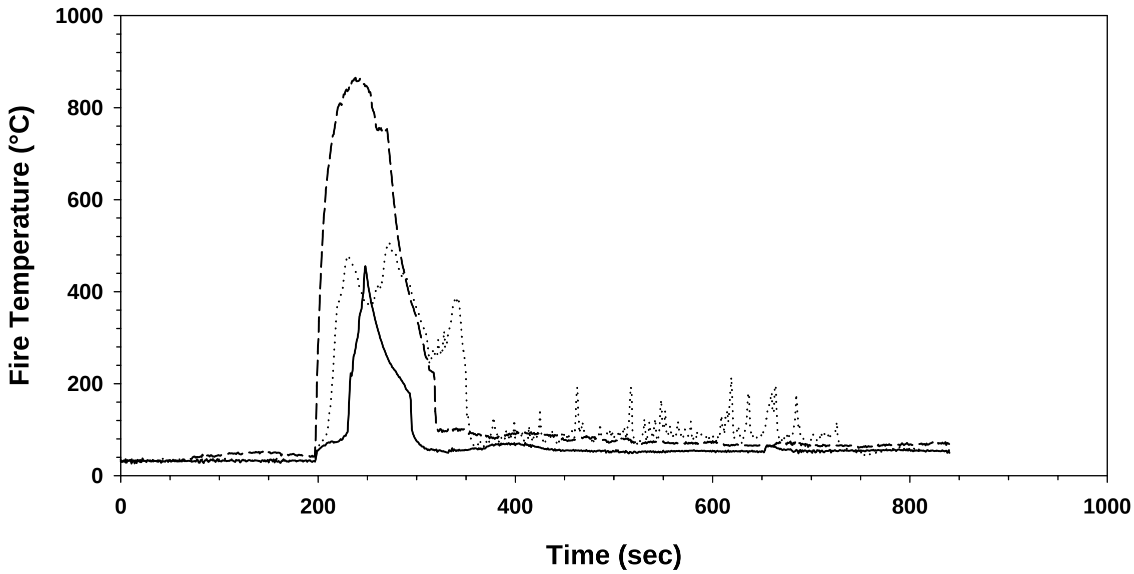
Ansul Test 13 - Heptane Spray on Side

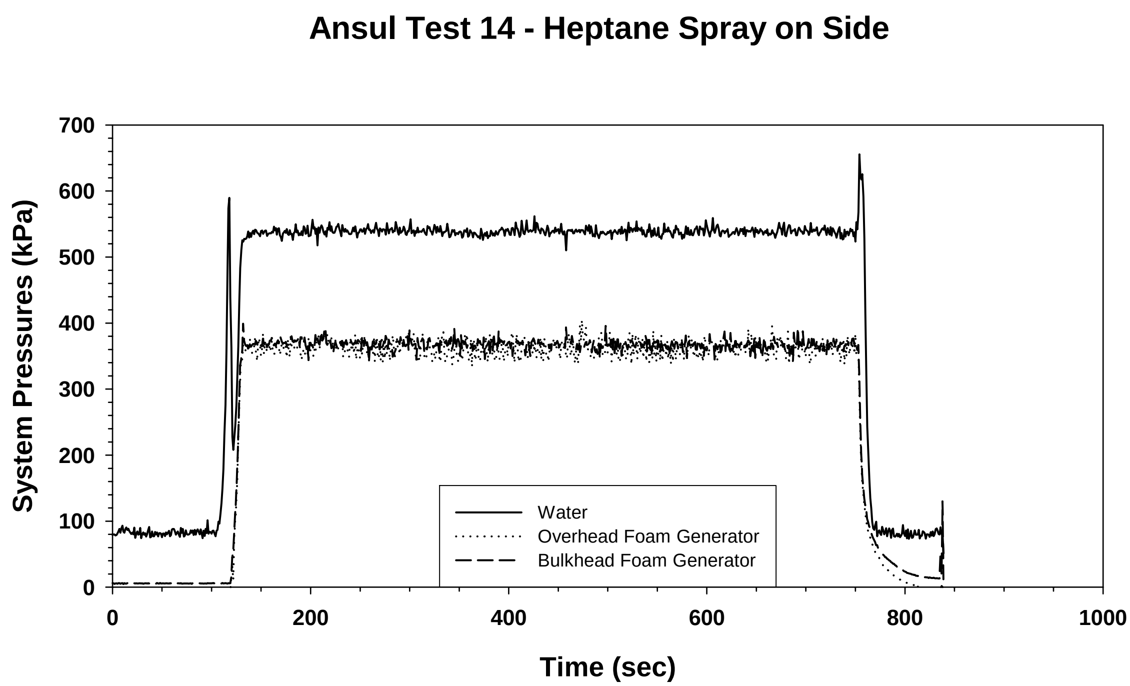


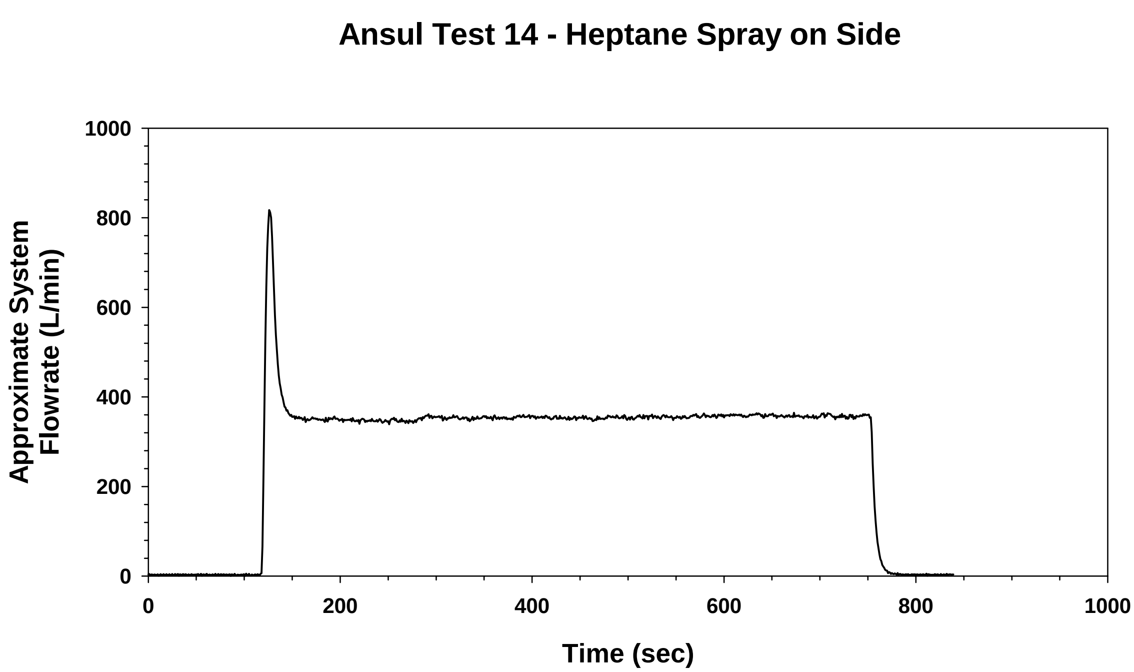
Ansul Test 13 - Heptane Spray on Side



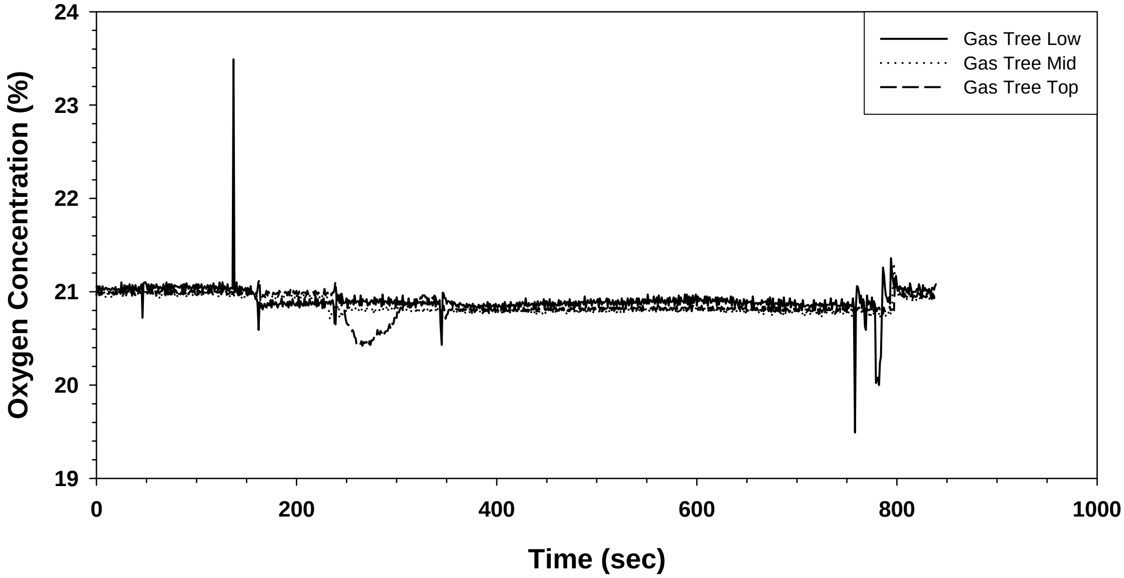
Ansul Test 13 - Heptane Spray on Side



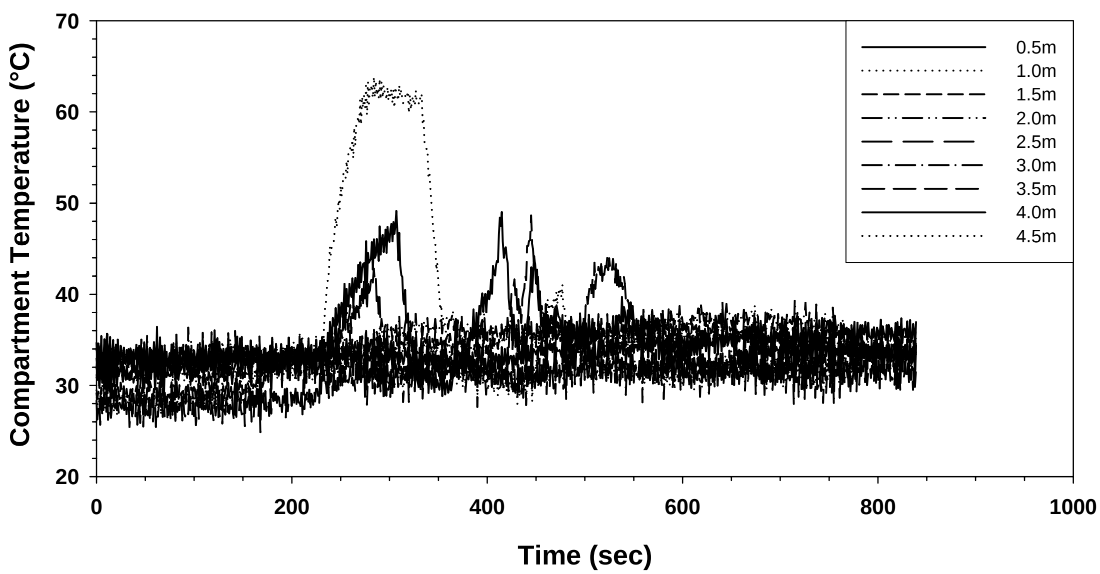

Ansul Test 14 - Heptane Spray on Side
System Pressures (kPa)
700
600
500
400
300
200
100
0
0
200
400
600
800
1000
Time (sec)
Water
Overhead Foam Generator
Bulkhead Foam Generator


Ansul Test 14 - Heptane Spray on Side
Approximate System Flowrate (L/min)
1000
800
600
400
200
0
0
200
400
600
800
1000
Time (sec)

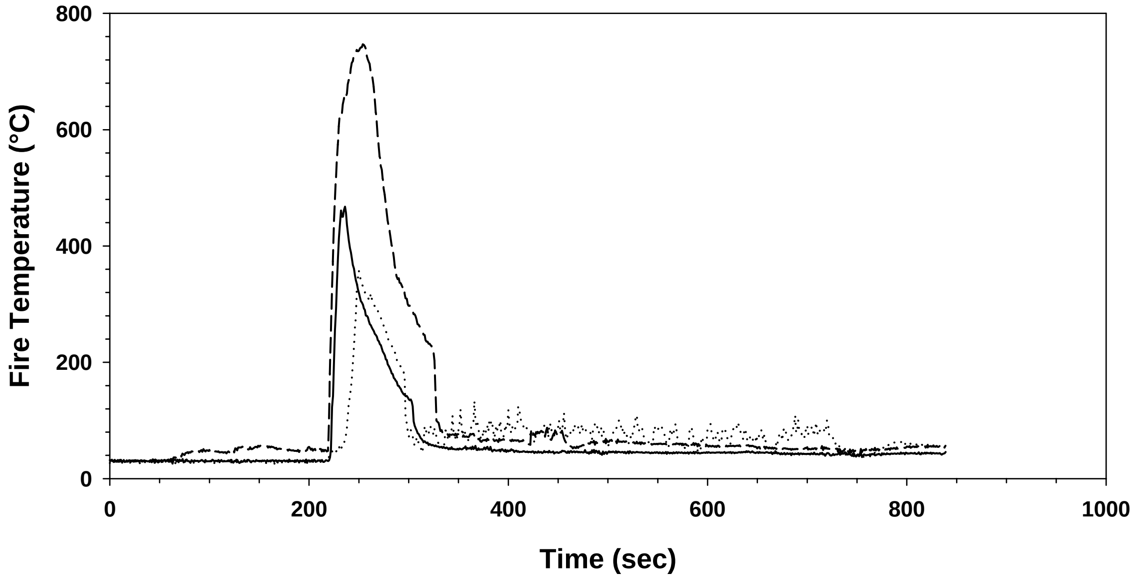
Ansul Test 14 - Heptane Spray on Side



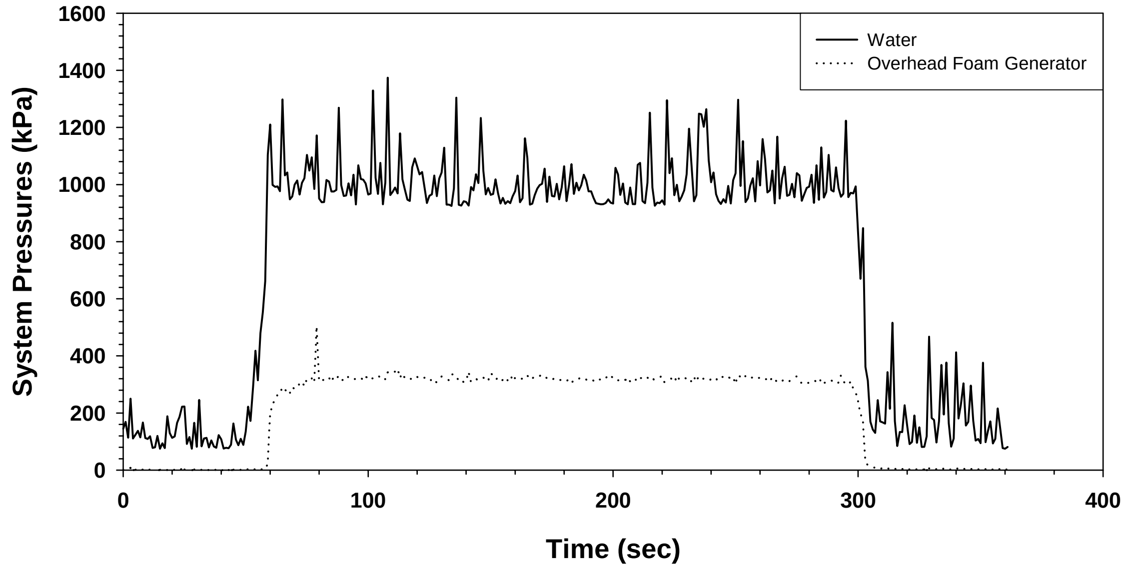
Ansul Test 14 - Heptane Spray on Side



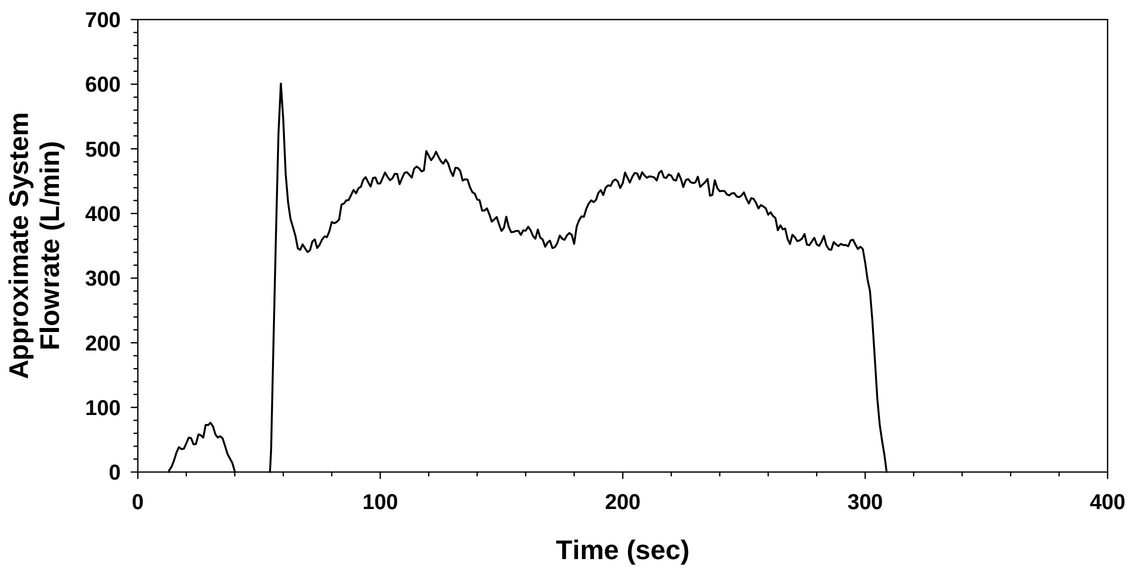
Ansul Test 14 - Heptane Spray on Side



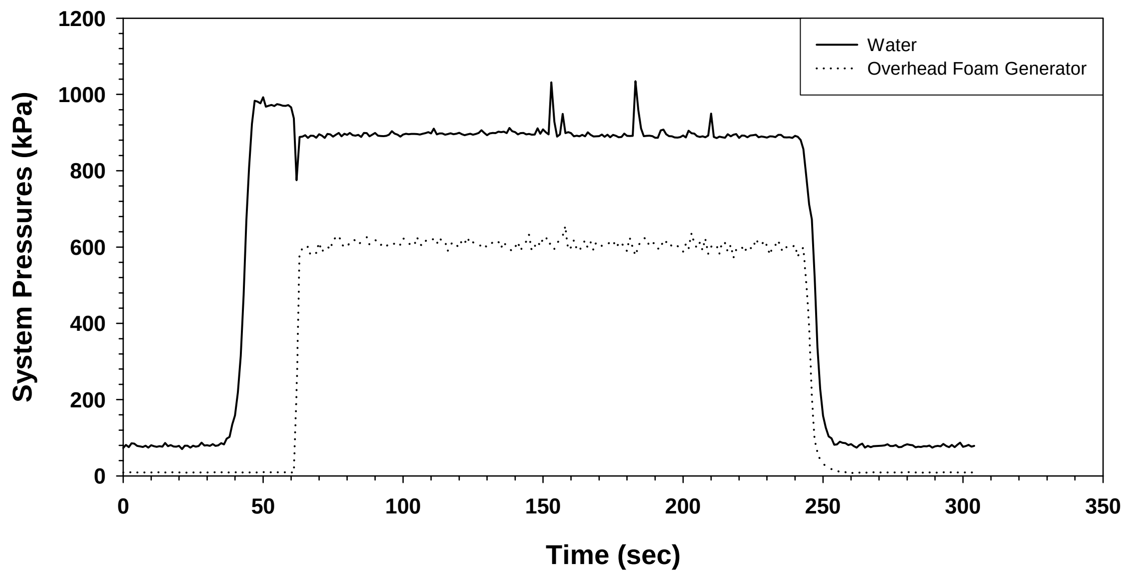
Buckeye Test 1 - Cold Discharge



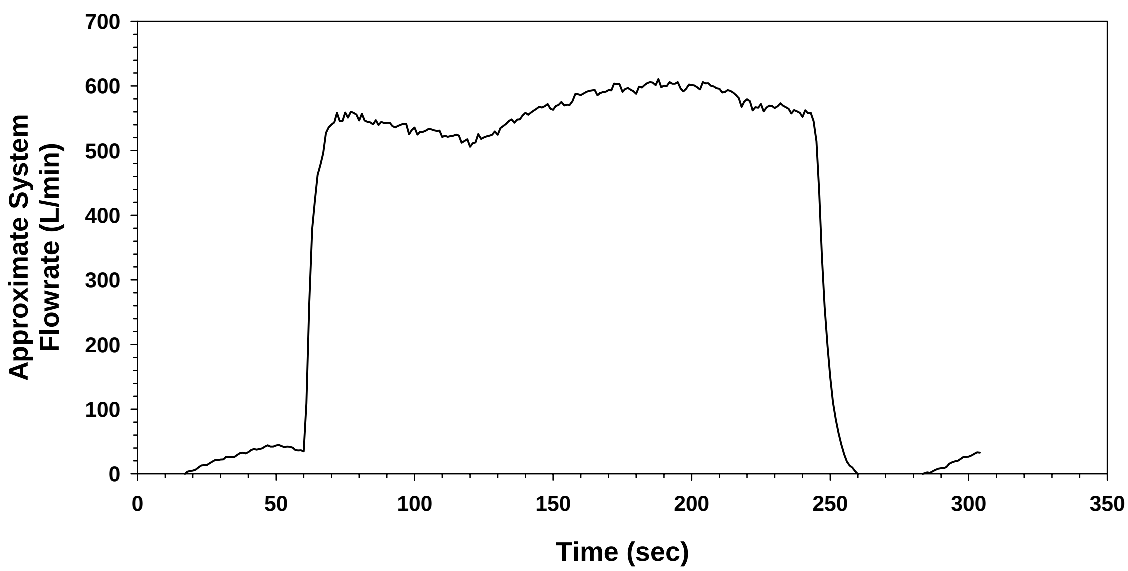
Buckeye Test 1 - Cold Discharge



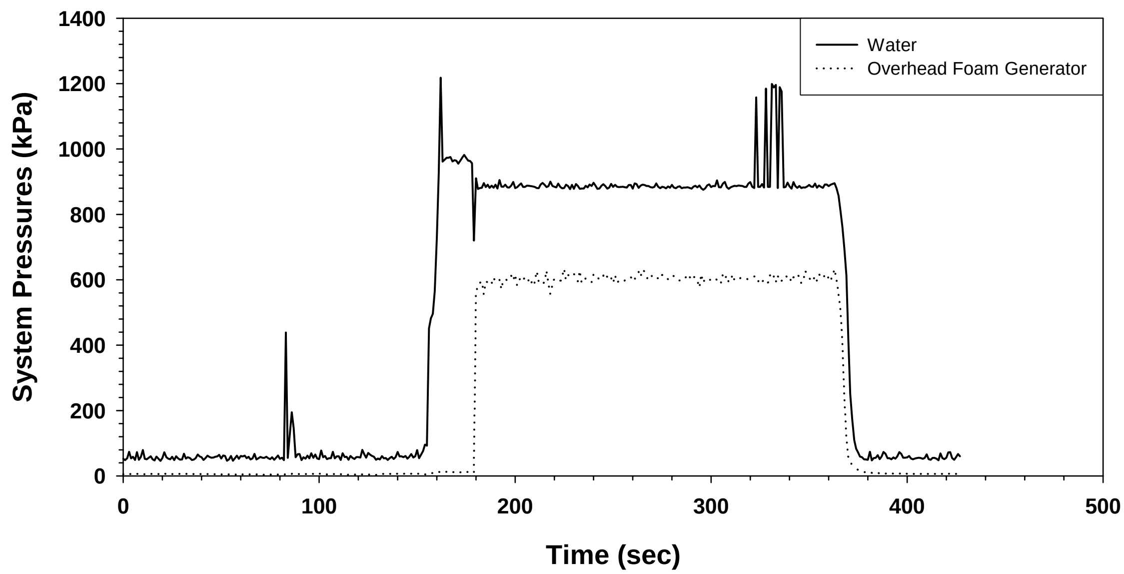
Buckeye Test 2 - Cold Discharge



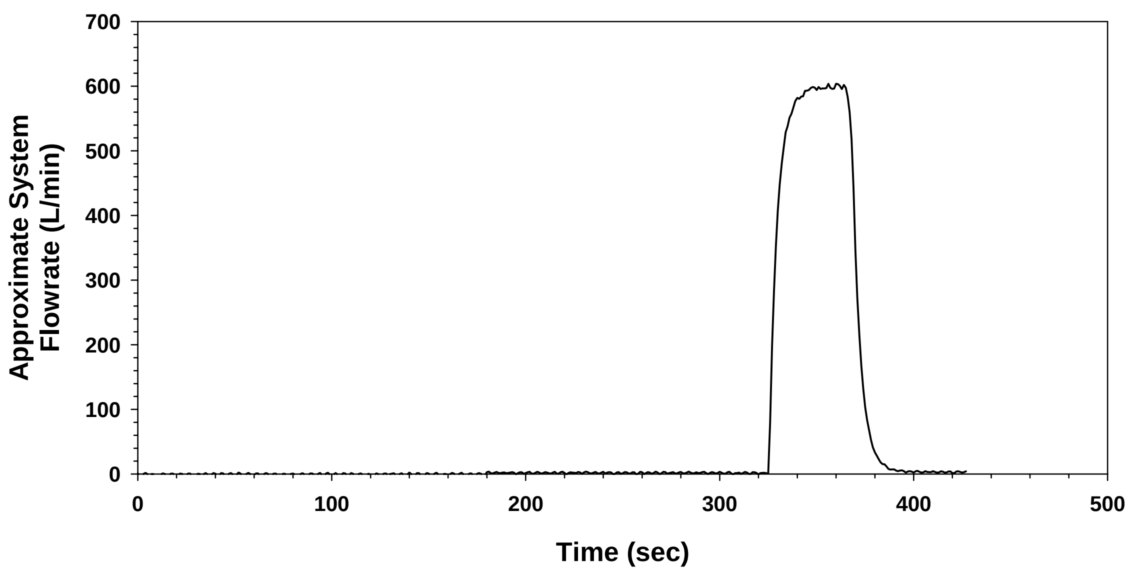
Buckeye Test 2 - Cold Discharge

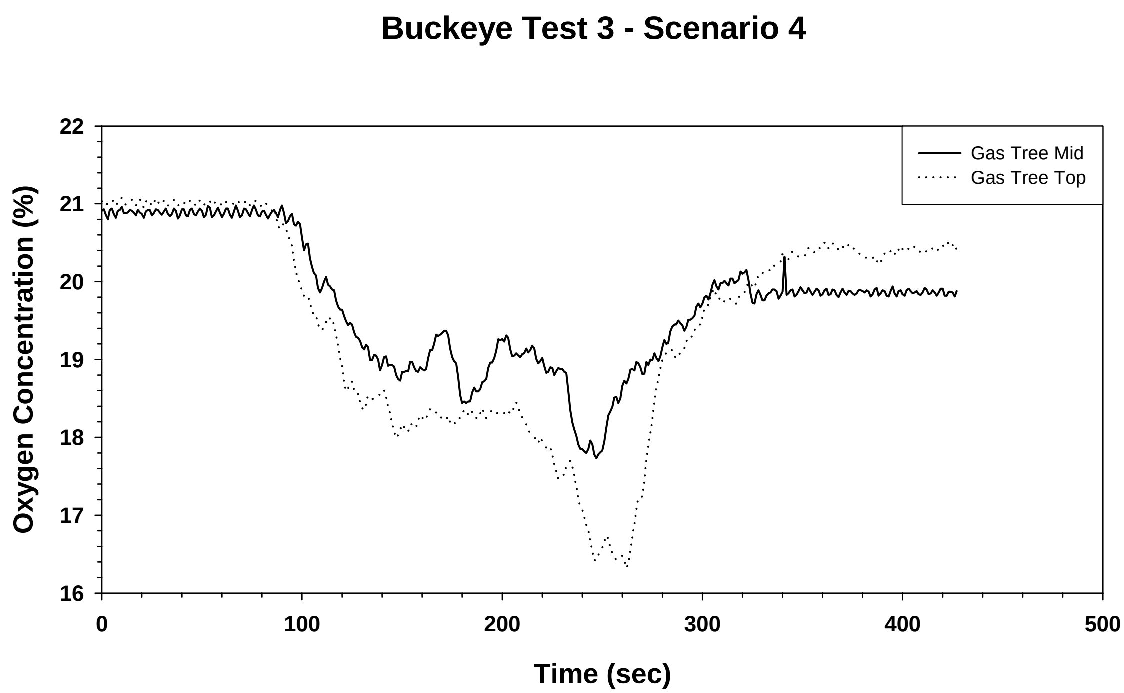


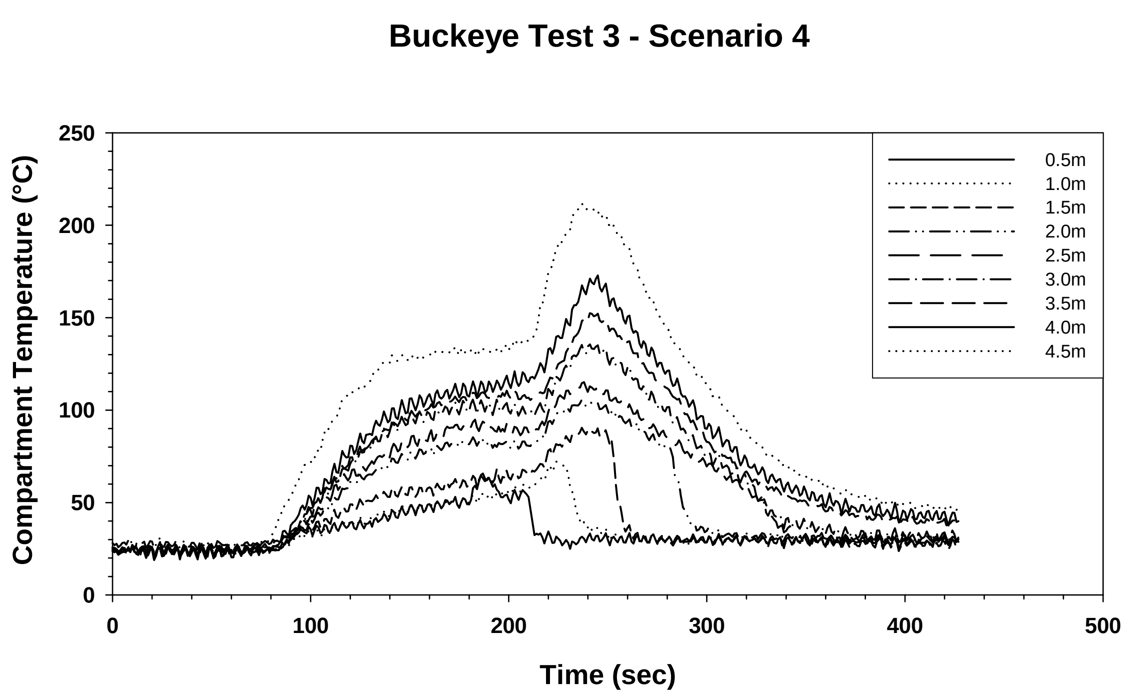
Buckeye Test 3 - Scenario 4

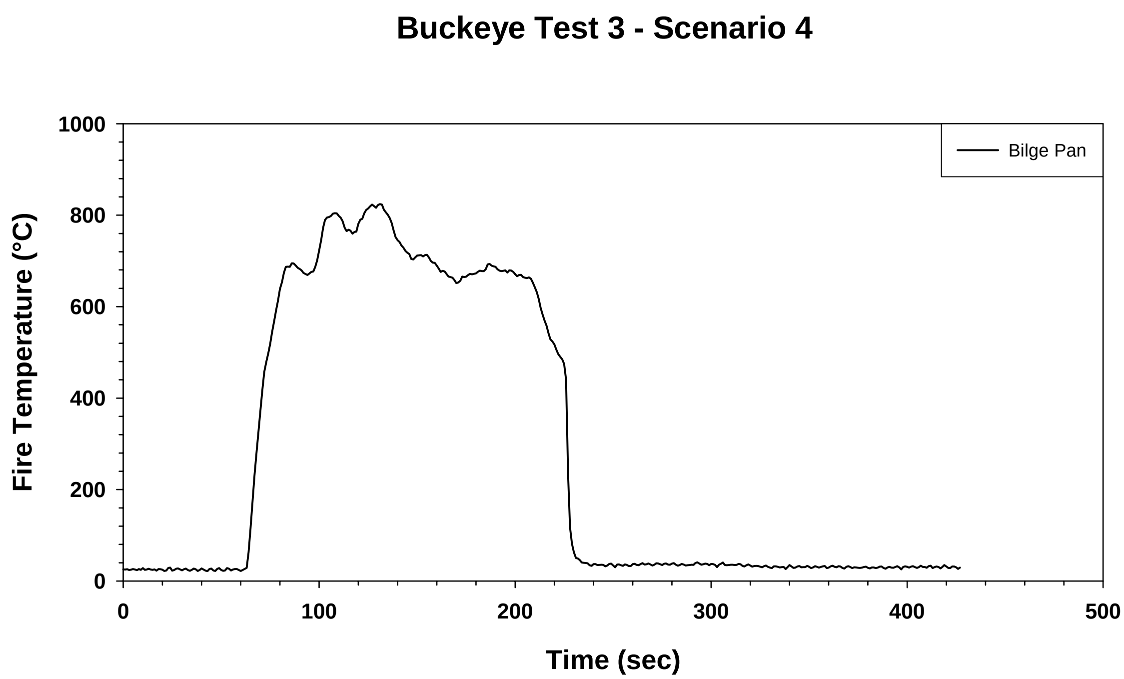


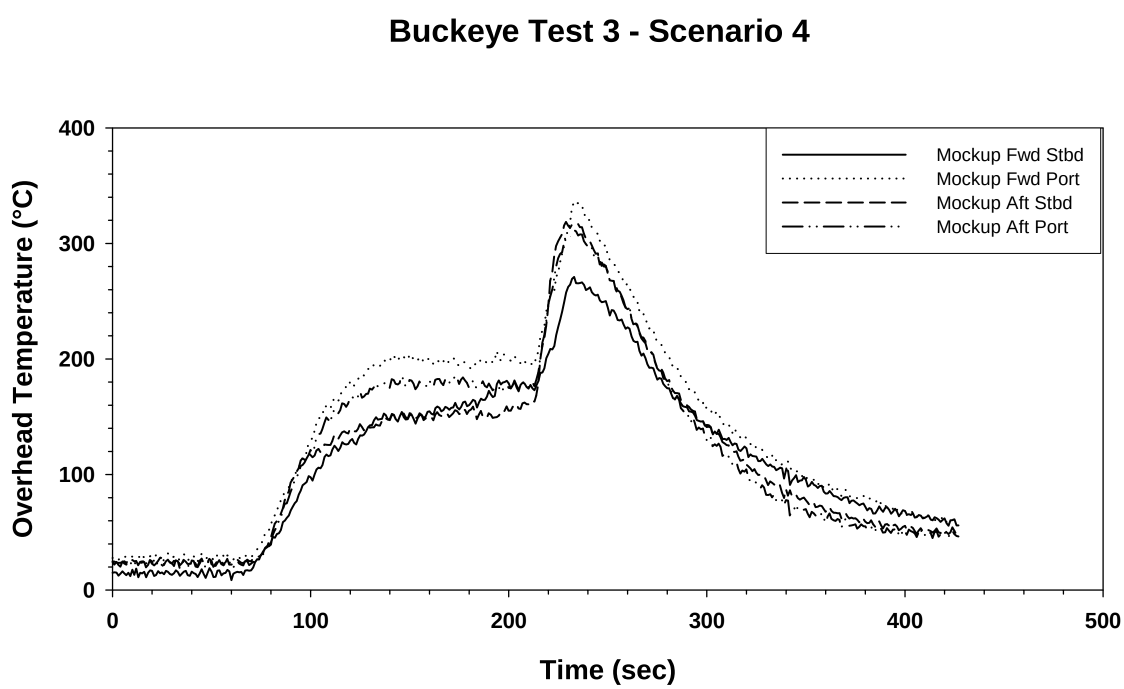
Buckeye Test 3 - Scenario 4



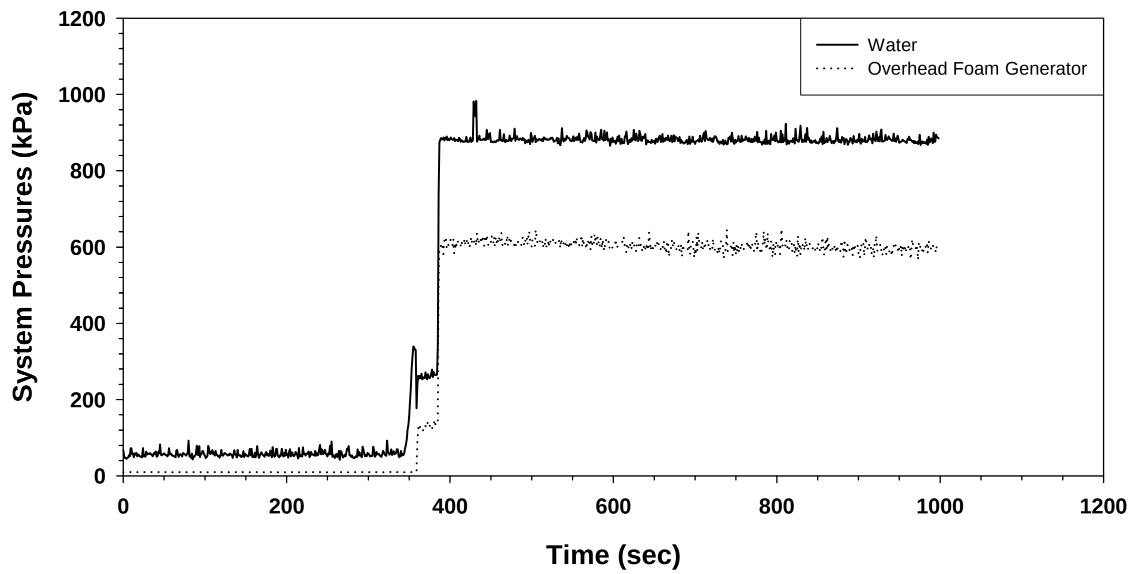

Buckeye Test 3 - Scenario 4
Gas Tree Mid
Gas Tree Top
Oxygen Concentration (%)
Time (sec)
22
21
20
19
18
17
16
0
100
200
300
400
500


Buckeye Test 3 - Scenario 4
0.5m
1.0m
1.5m
2.0m
2.5m
3.0m
3.5m
4.0m
4.5m
Compartment Temperature (°C)
Time (sec)
250
200
150
100
50
0
0
100
200
300
400
500

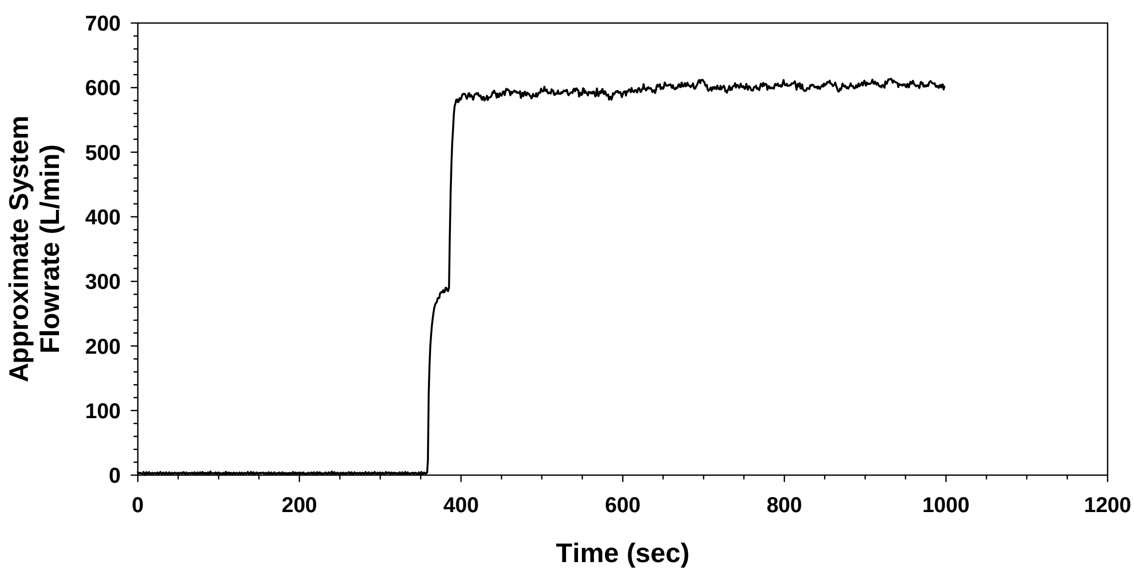

Buckeye Test 3 - Scenario 4
Fire Temperature (°C)
1000
800
600
400
200
0
0
100
200
300
400
500
Time (sec)
Bilge Pan


Buckeye Test 3 - Scenario 4
Overhead Temperature (°C)
400
300
200
100
0
0
100
200
300
400
500
Time (sec)
Mockup Fwd Stbd
Mockup Fwd Port
Mockup Aft Stbd
Mockup Aft Port

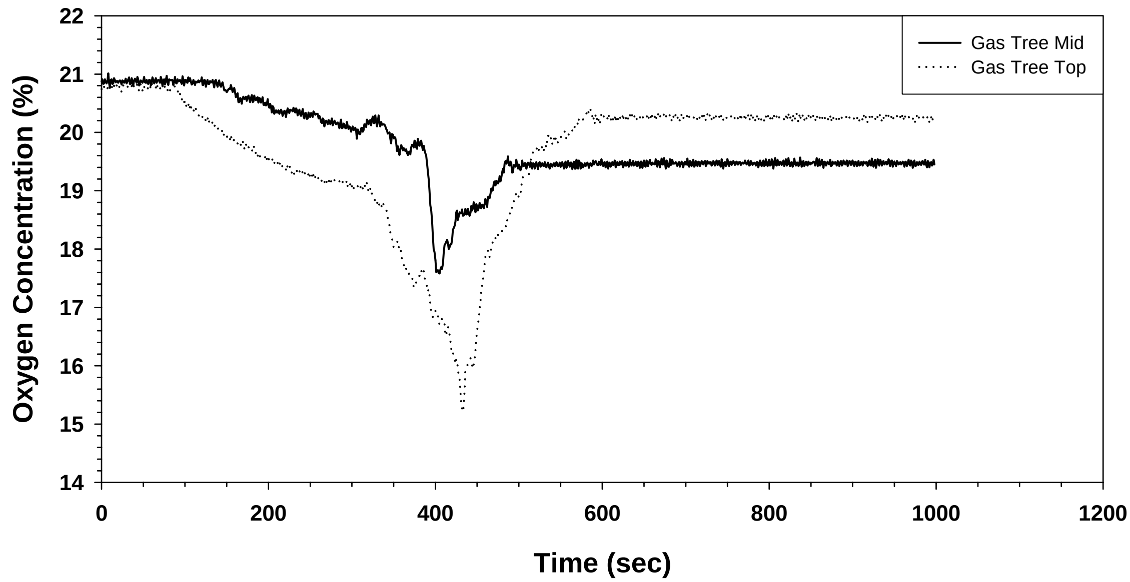
Buckeye Test 4 - Scenario 3



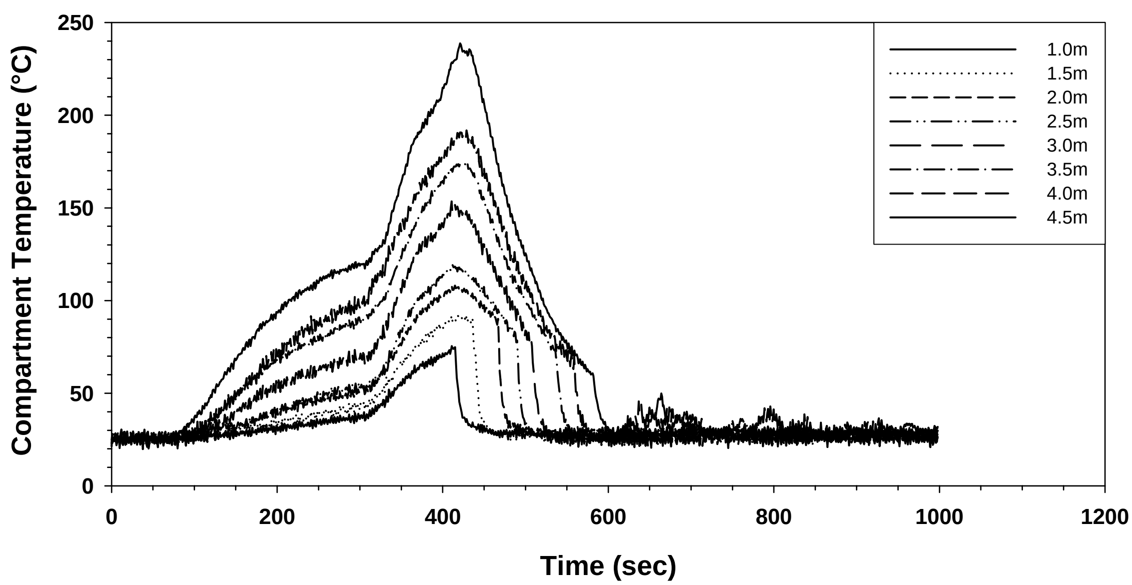
Buckeye Test 4 - Scenario 3



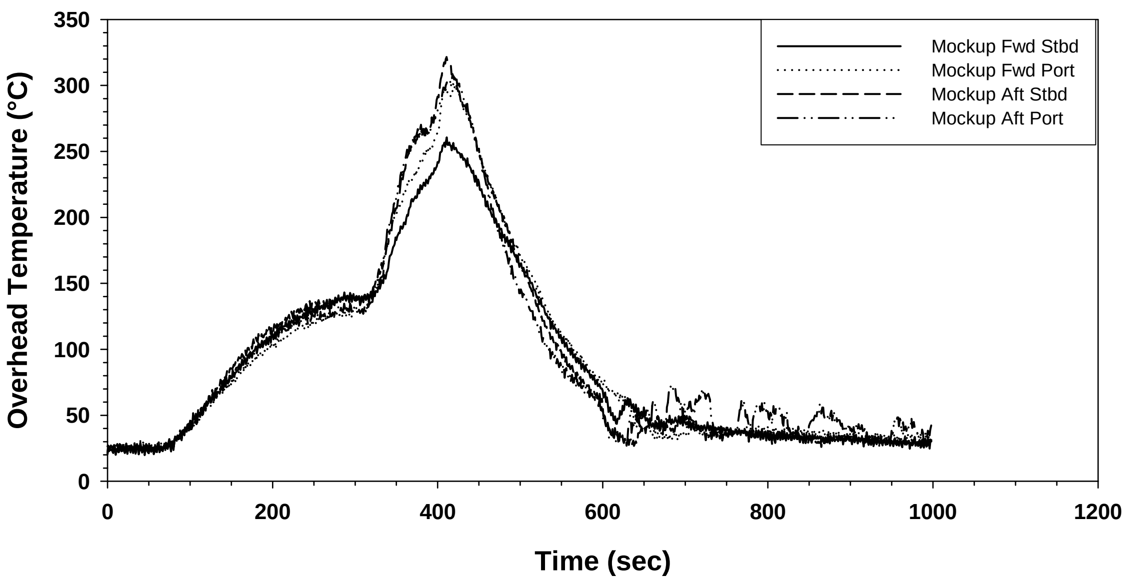
Buckeye Test 4 - Scenario 3



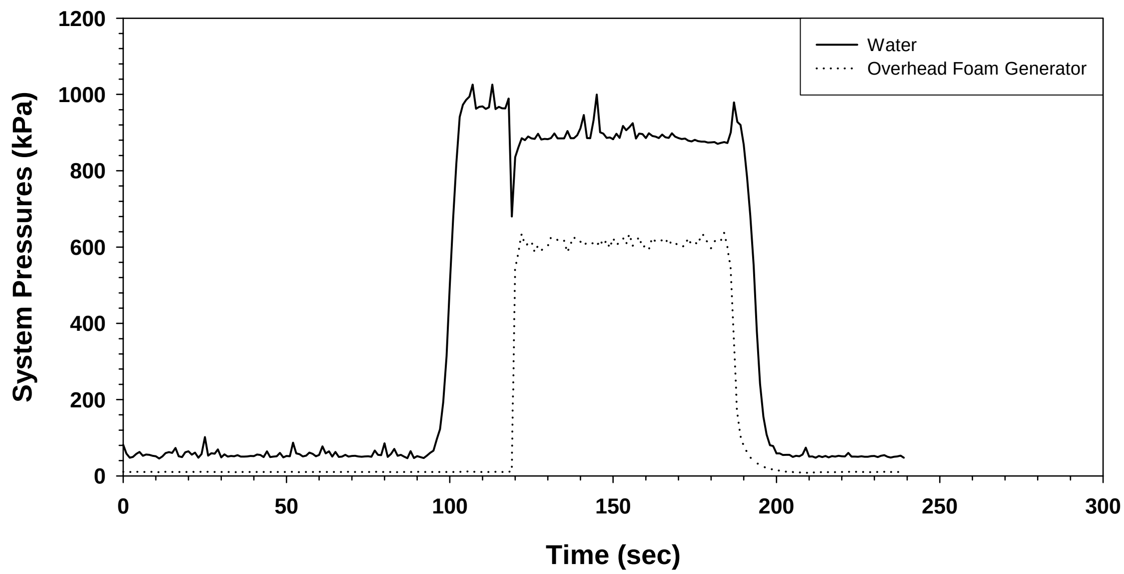
Buckeye Test 4 - Scenario 3



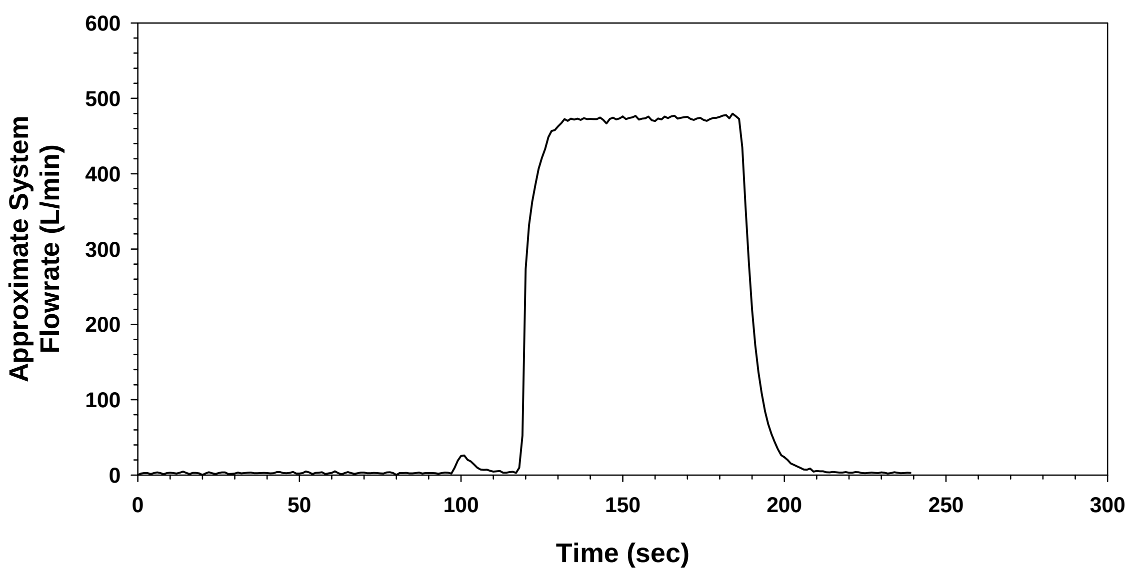
Buckeye Test 4 - Scenario 3



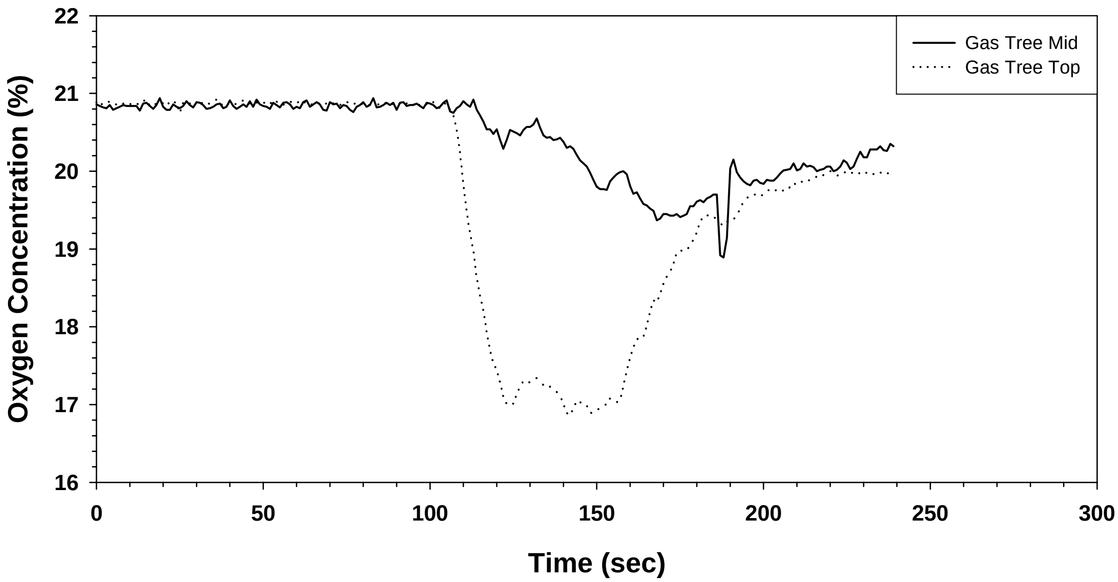
Buckeye Test 5 - Diesel Spray on Deck



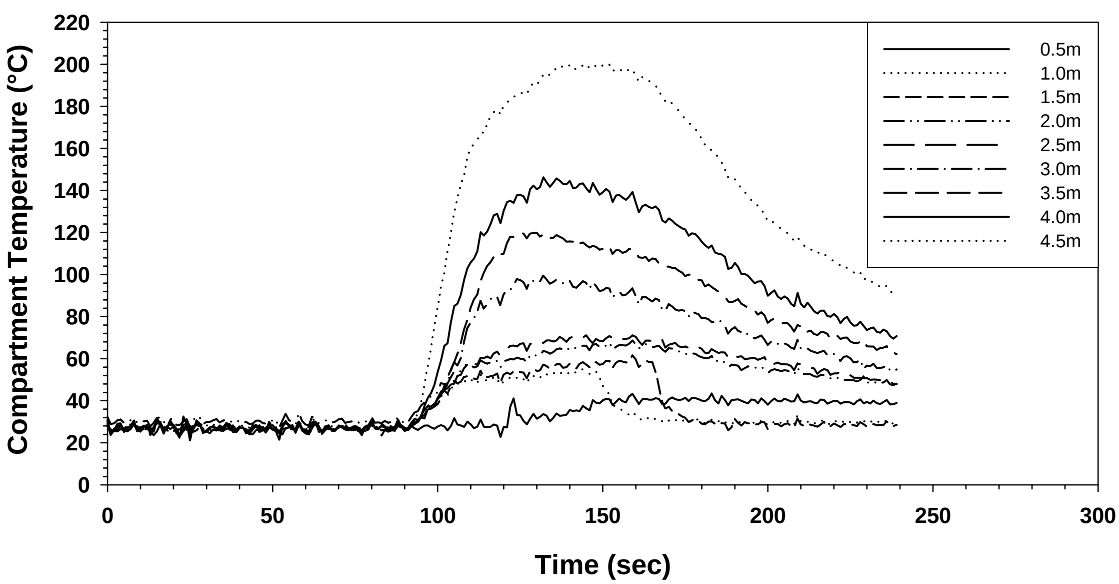
Buckeye Test 5 - Diesel Spray on Deck



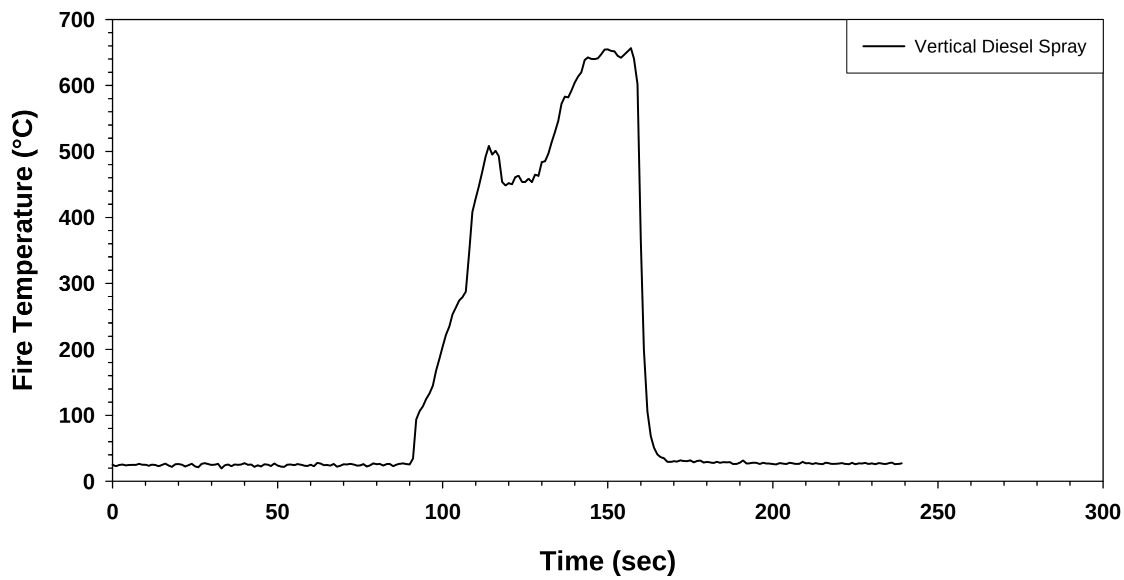
Buckeye Test 5 - Diesel Spray on Deck



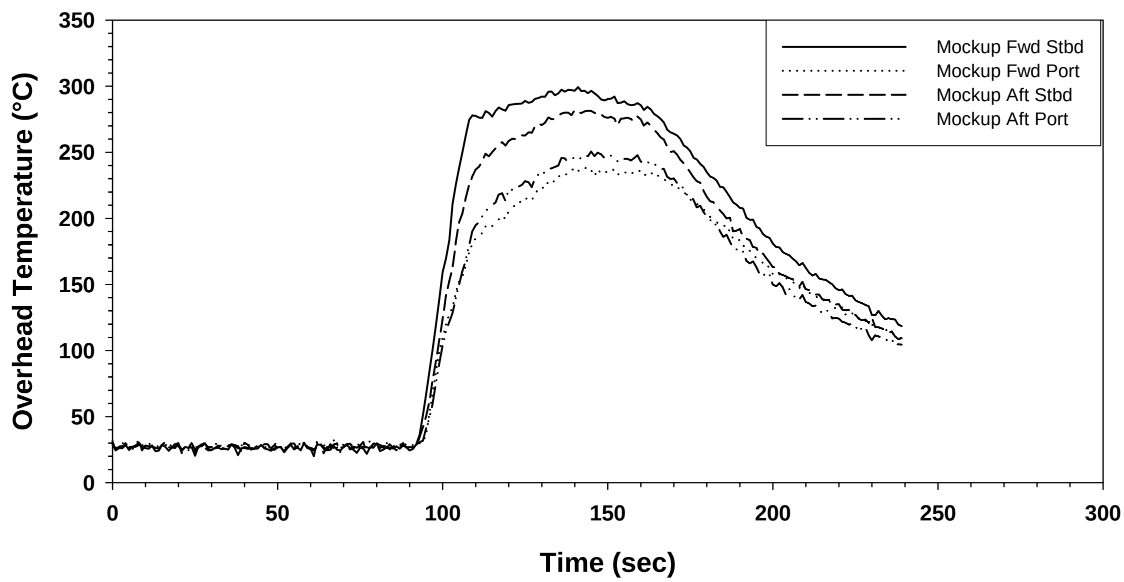
Buckeye Test 5 - Diesel Spray on Deck



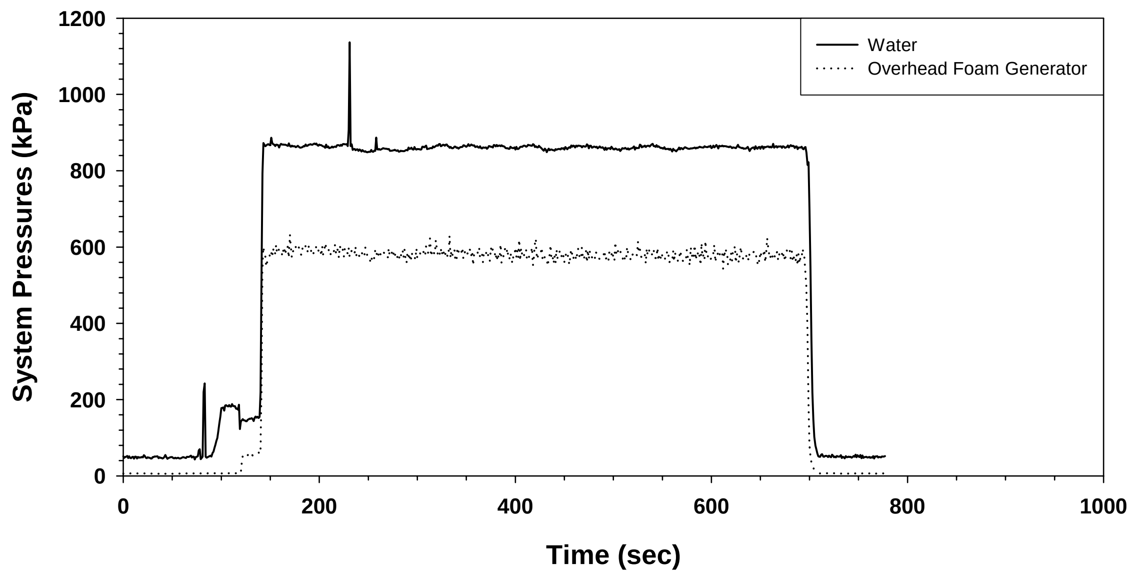
Buckeye Test 5 - Diesel Spray on Deck



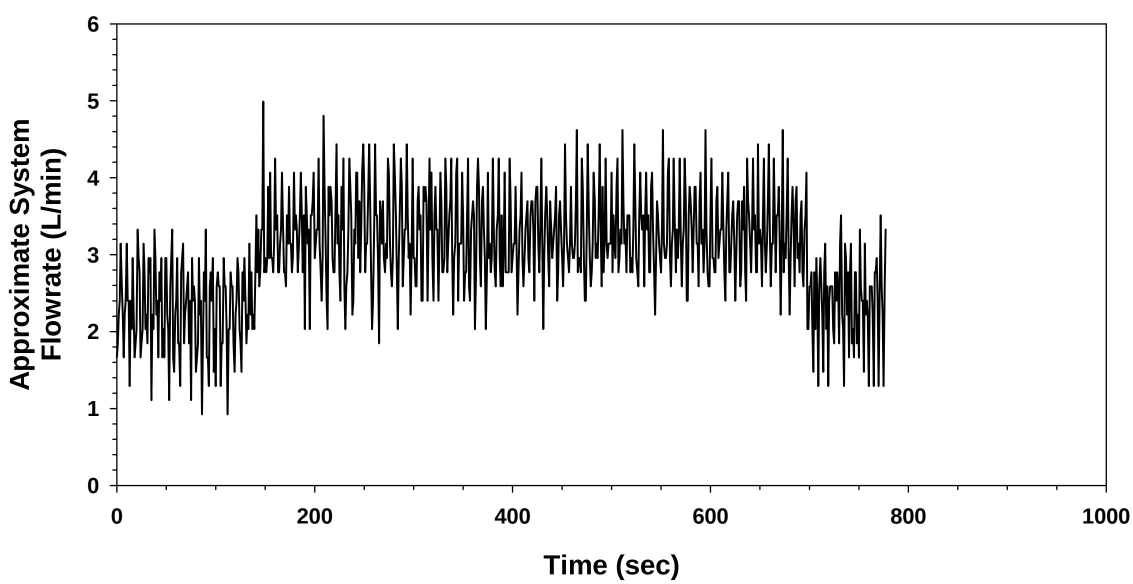
Buckeye Test 5 - Diesel Spray on Deck



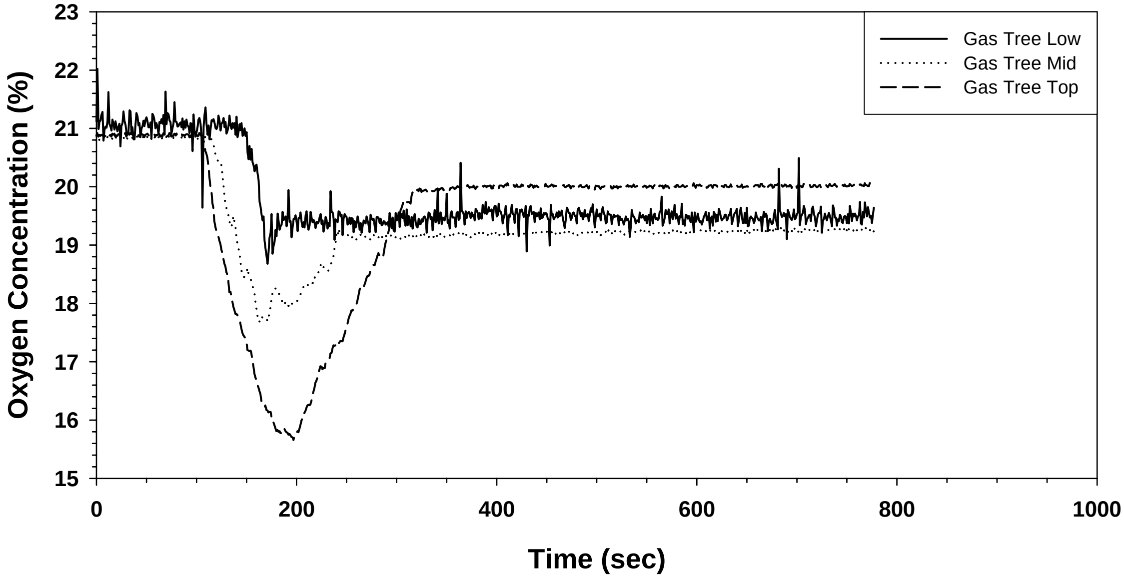
Buckeye Test 6 - Heptane Spray on Deck



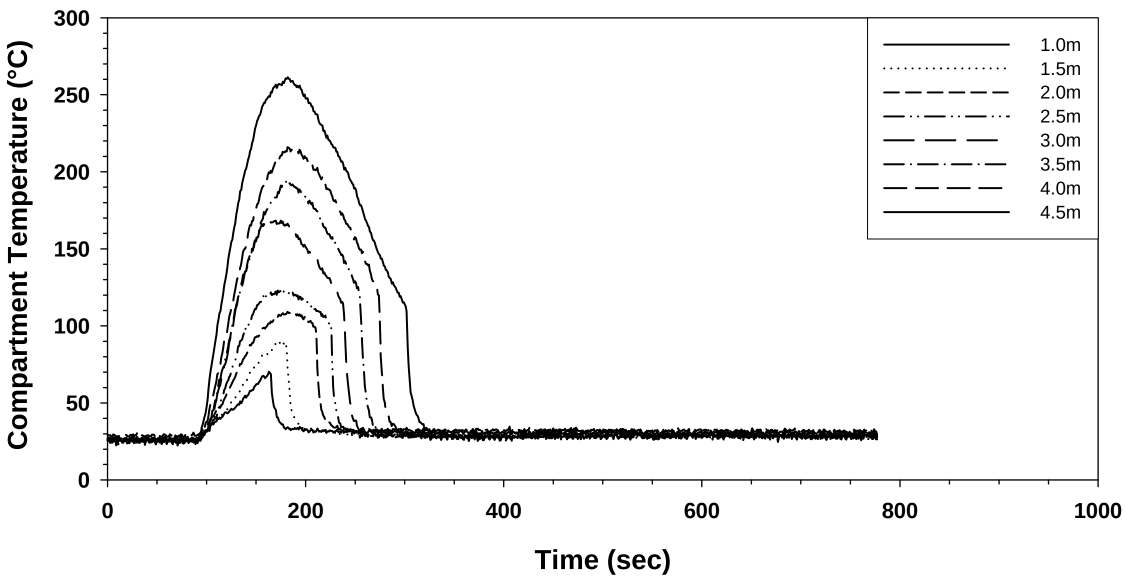
Buckeye Test 6 - Heptane Spray on Deck



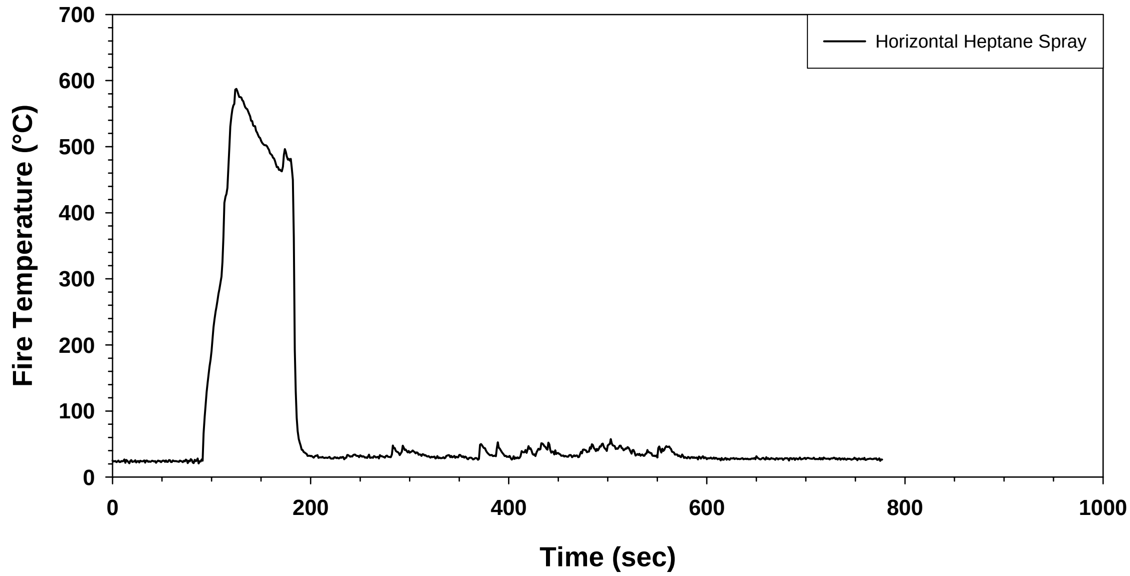
Buckeye Test 6 - Heptane Spray on Deck



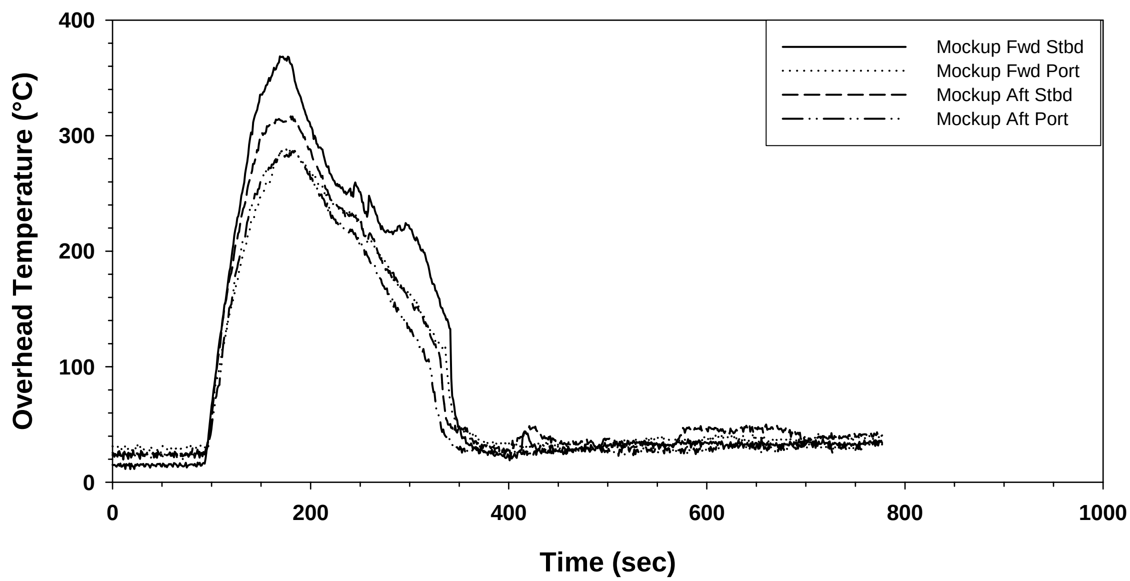
Buckeye Test 6 - Heptane Spray on Deck

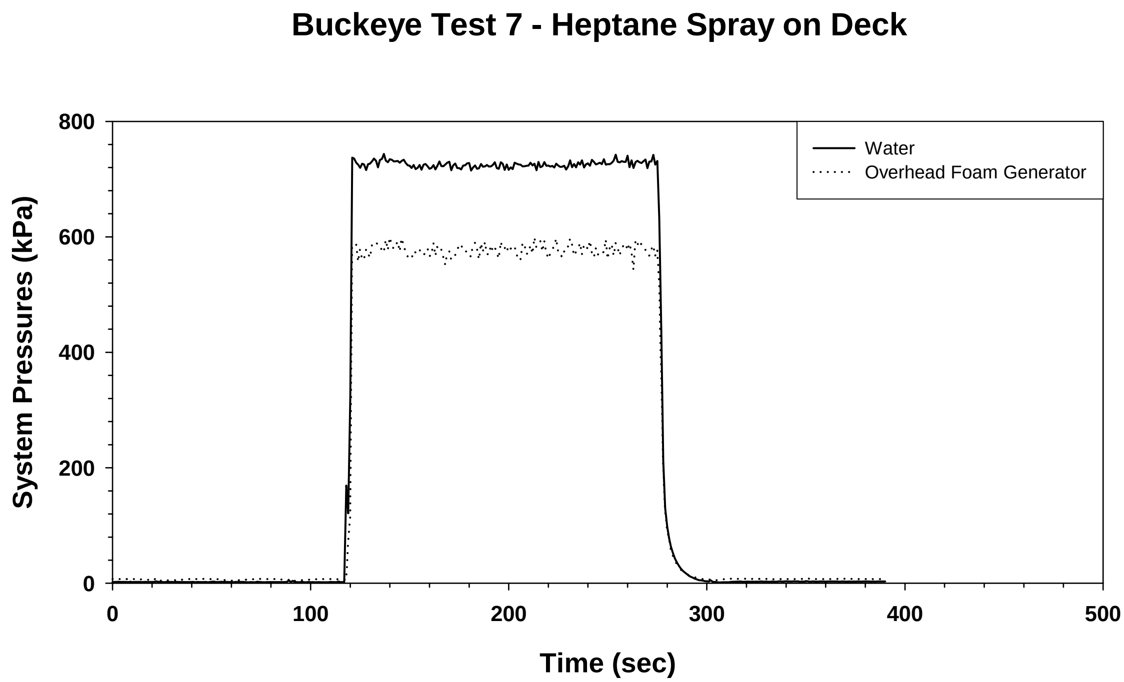


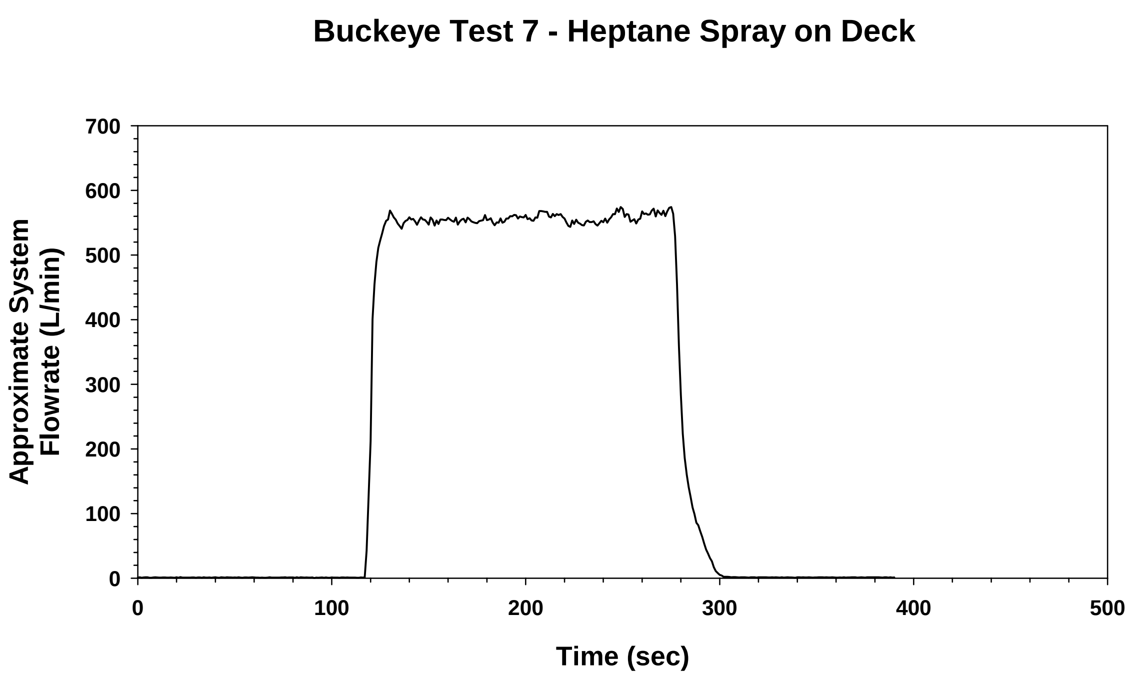
Buckeye Test 6 - Heptane Spray on Deck



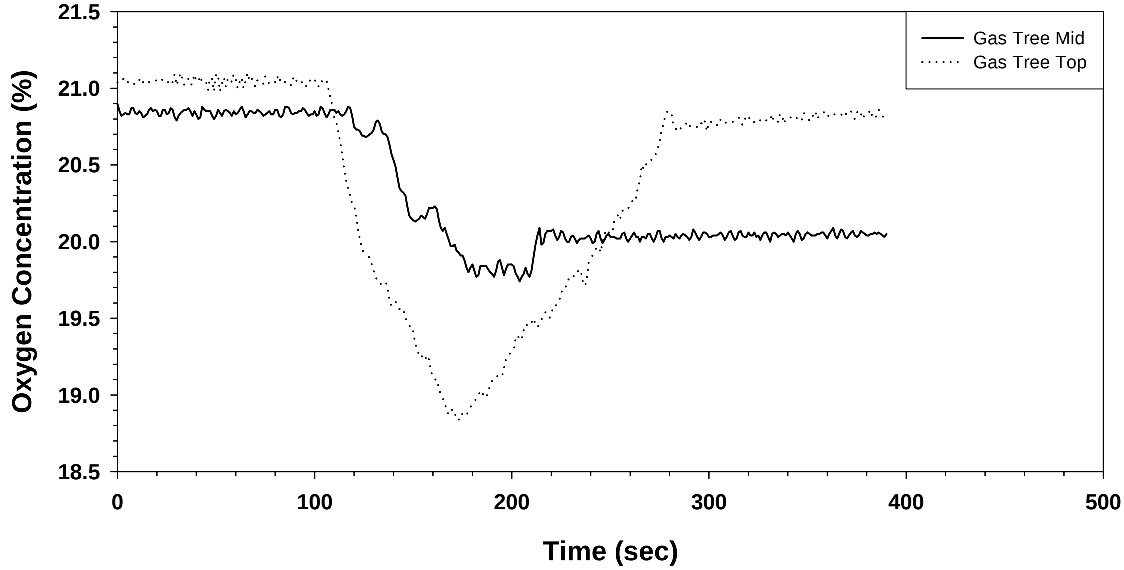
Buckeye Test 6 - Heptane Spray on Deck



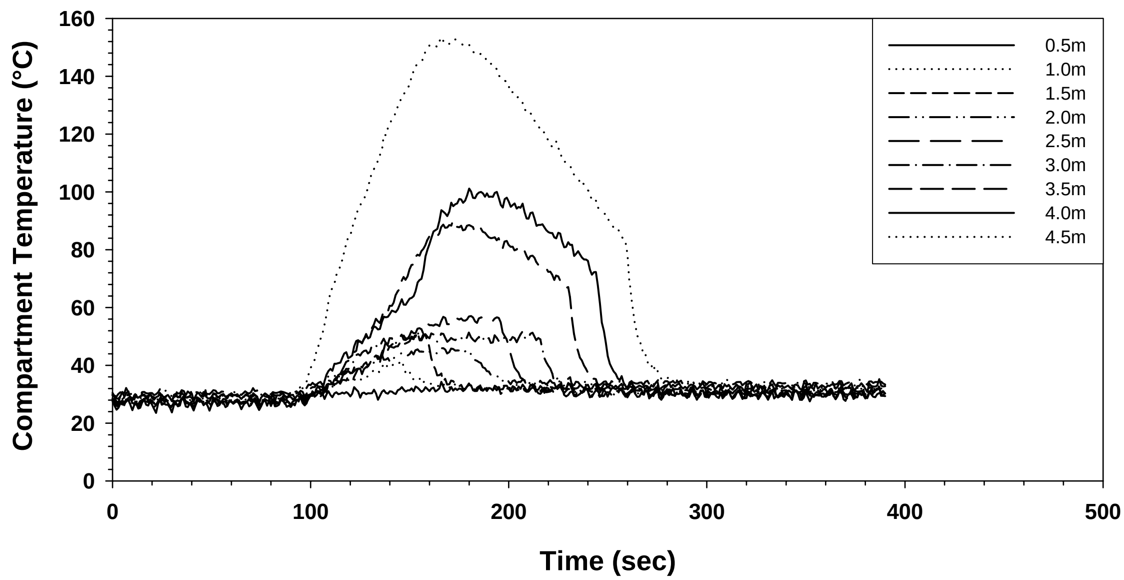

Buckeye Test 7 - Heptane Spray on Deck
System Pressures (kPa)
Time (sec)
Water
Overhead Foam Generator
0
200
400
600
800
0
100
200
300
400
500


Buckeye Test 7 - Heptane Spray on Deck
Approximate System Flowrate (L/min)
Time (sec)
0
100
200
300
400
500
600
700
0
100
200
300
400
500

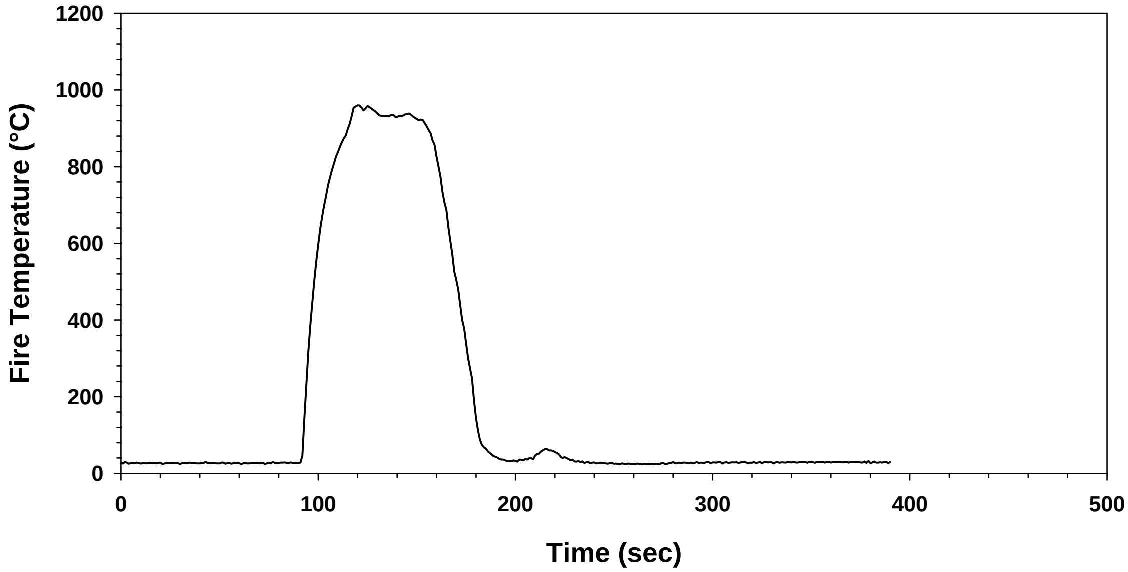
Buckeye Test 7 - Heptane Spray on Deck



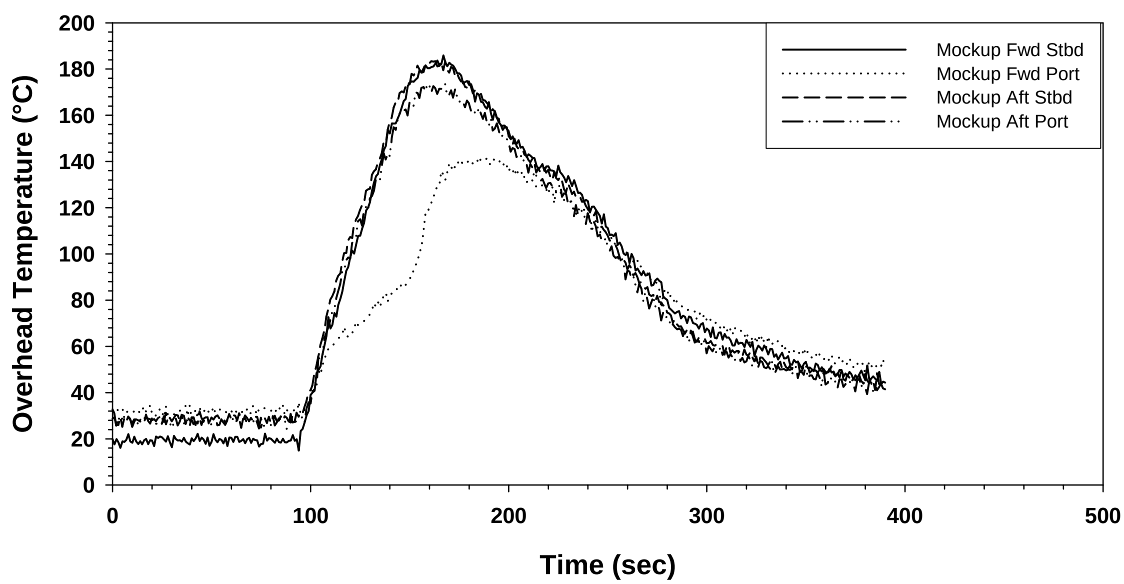
Buckeye Test 7 - Heptane Spray on Deck



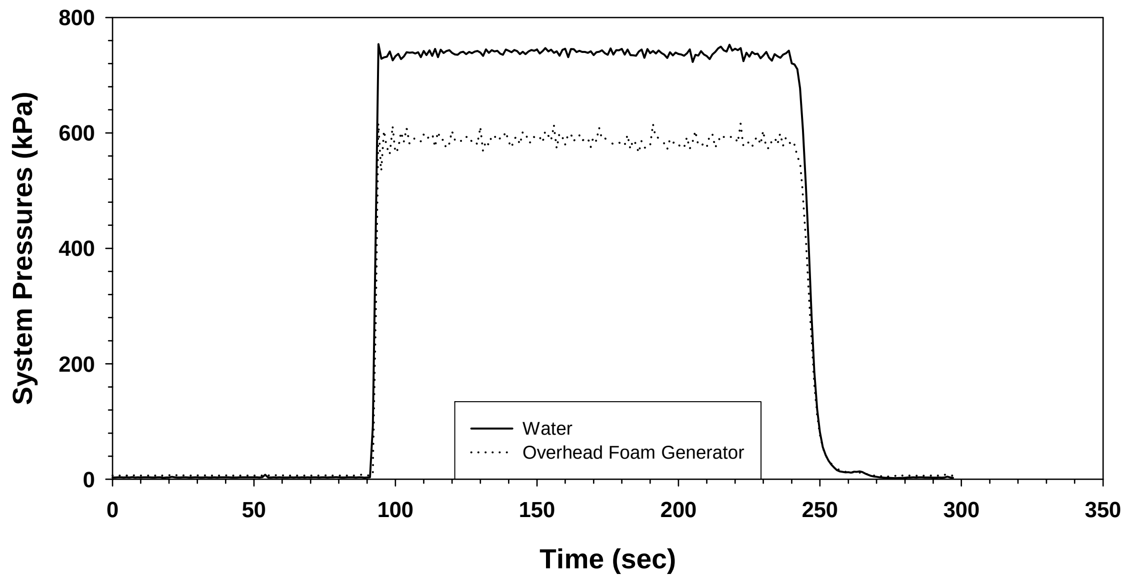
Buckeye Test 7 - Heptane Spray on Deck



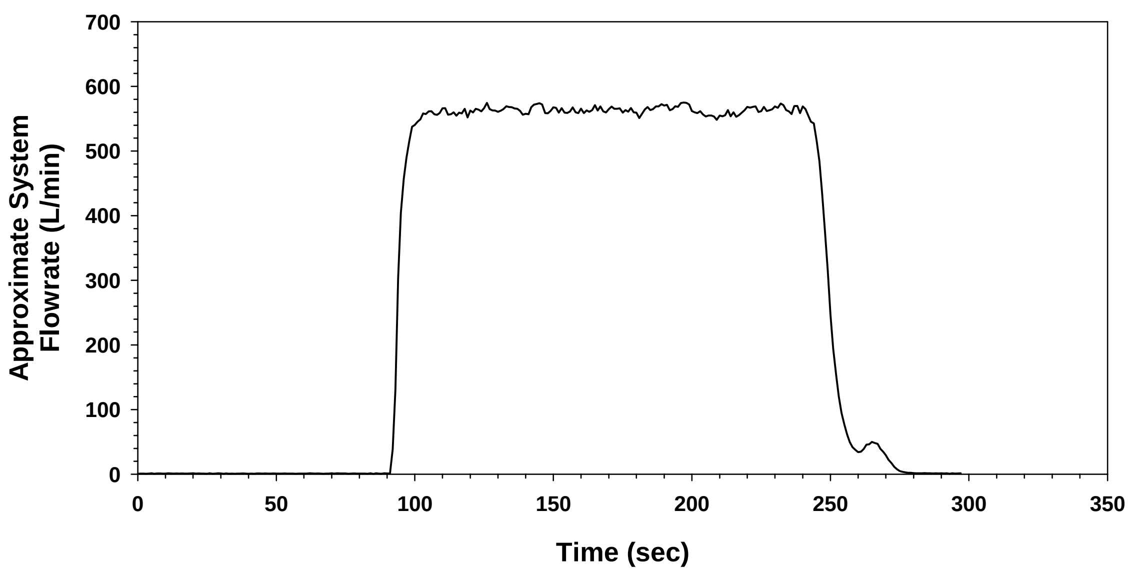
Buckeye Test 7 - Heptane Spray on Deck



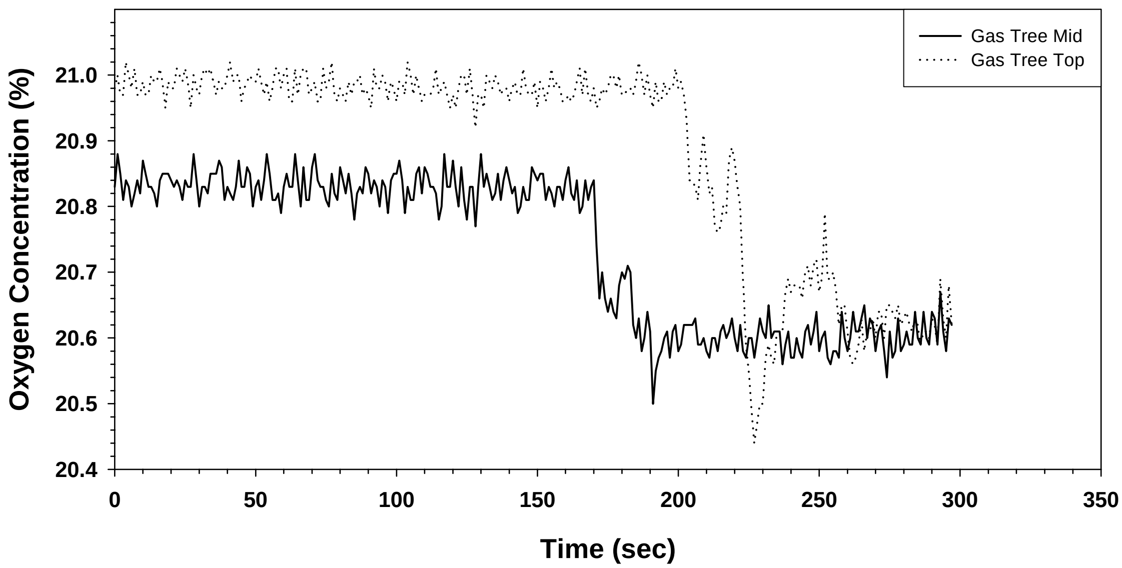
Buckeye Test 8 - Diesel Spray on Top



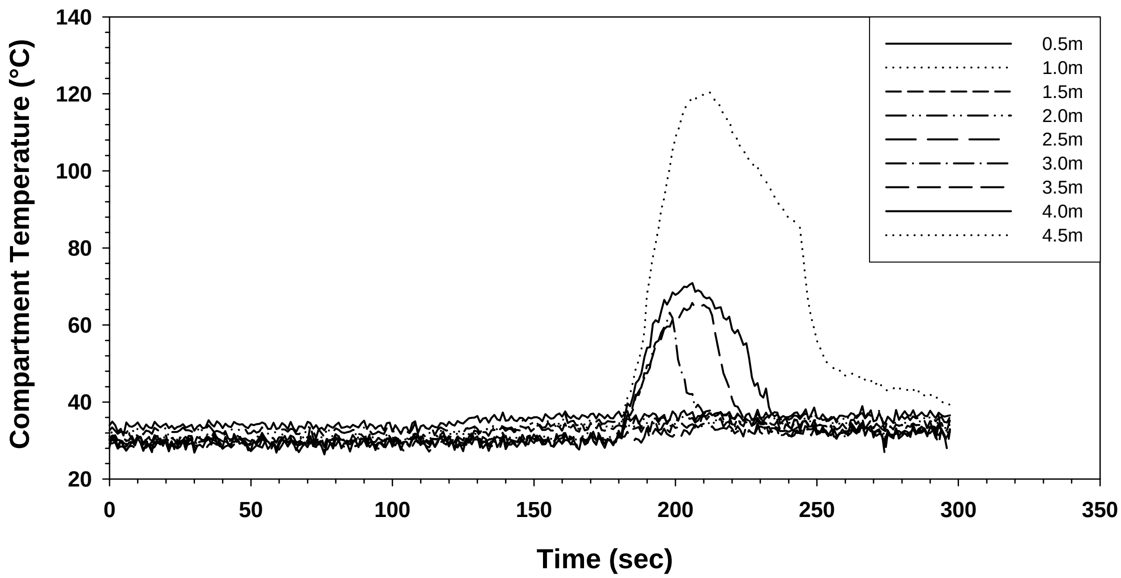
Buckeye Test 8 - Diesel Spray on Top

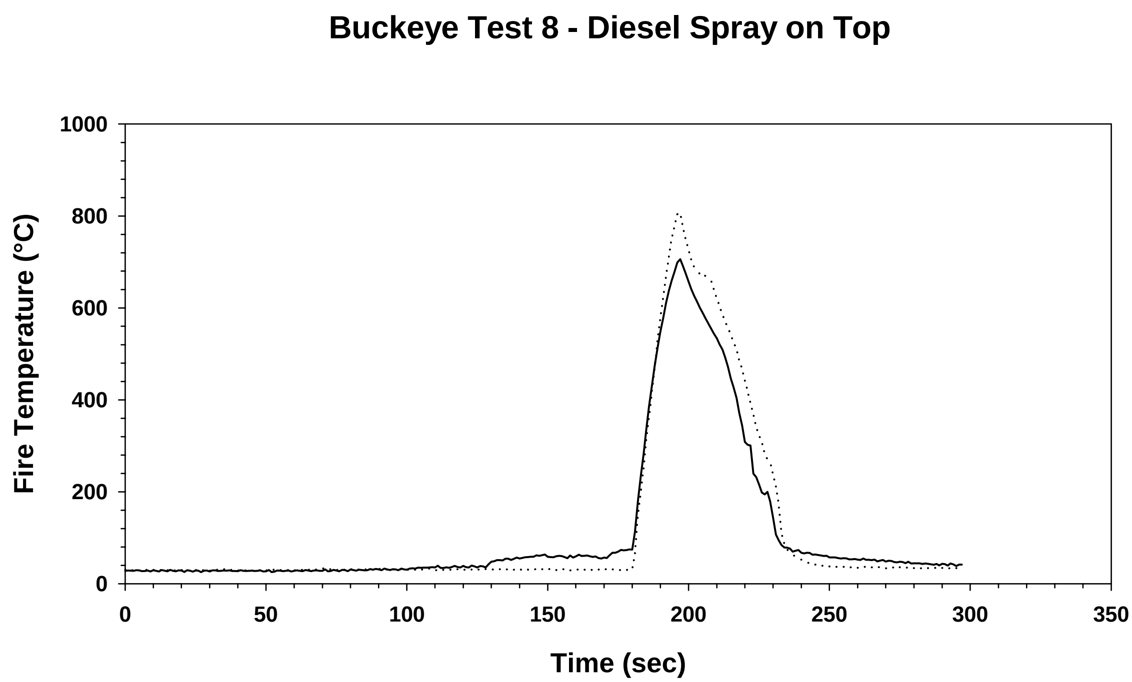


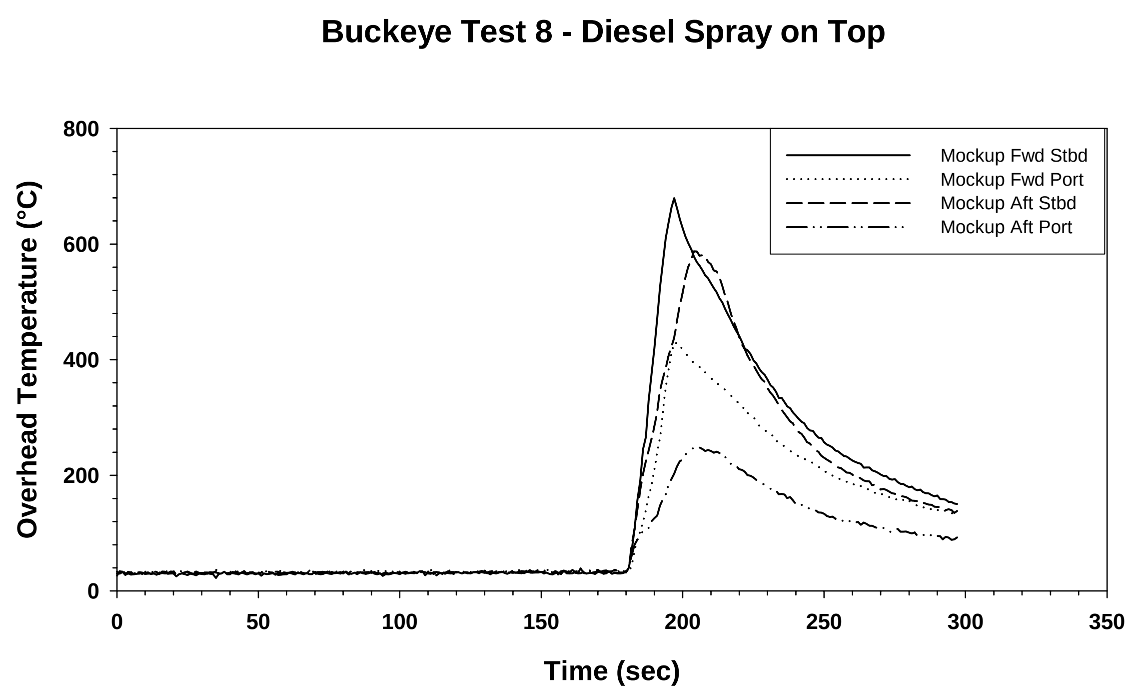
Buckeye Test 8 - Diesel Spray on Top



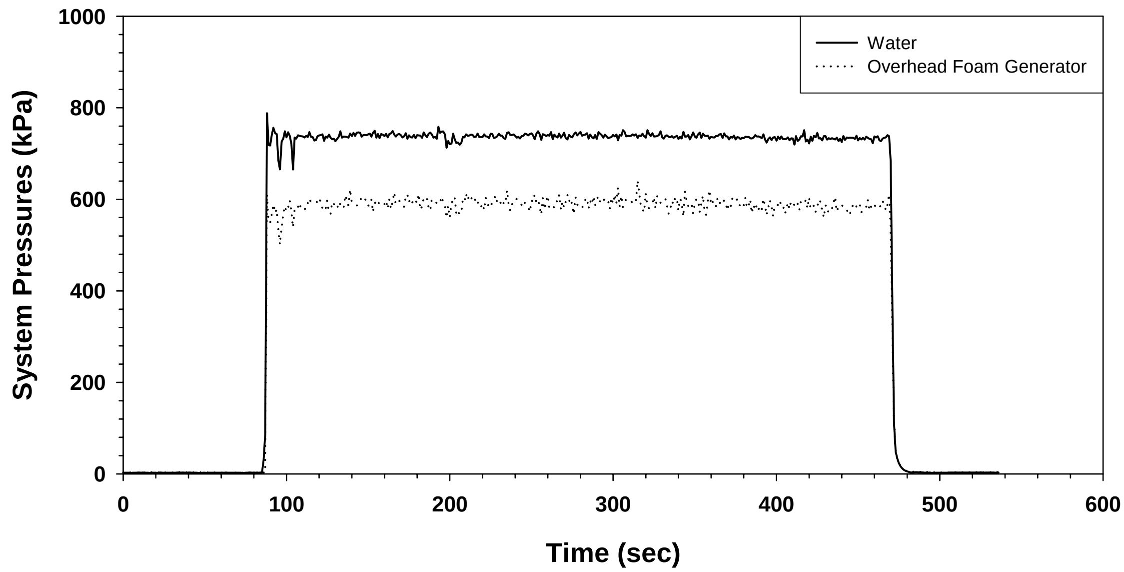
Buckeye Test 8 - Diesel Spray on Top



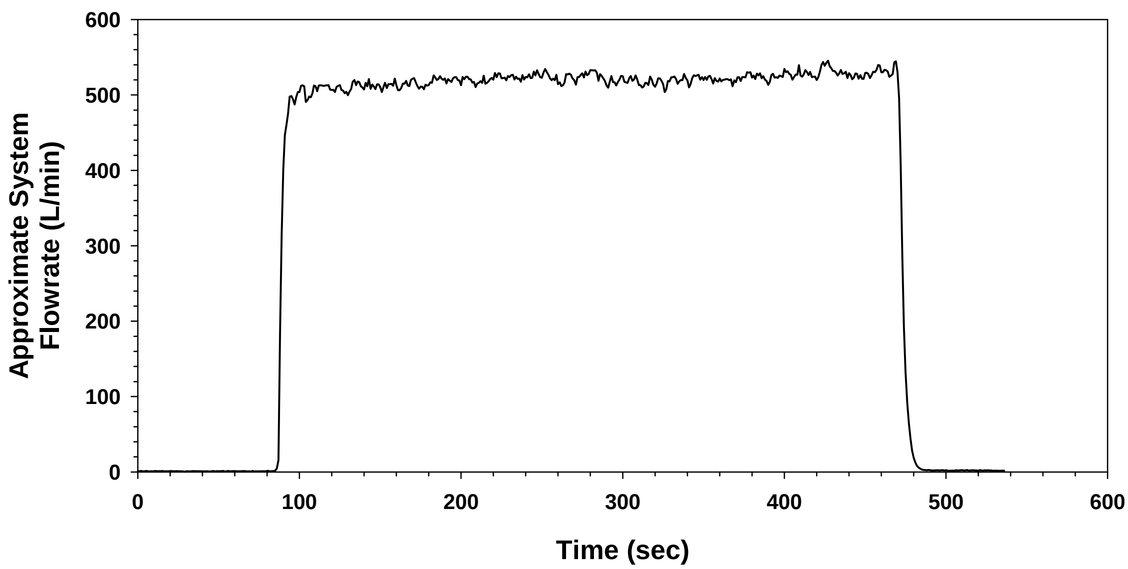

Buckeye Test 8 - Diesel Spray on Top
Fire Temperature (°C)
0
200
400
600
800
1000
0
50
100
150
200
250
300
350
Time (sec)


Buckeye Test 8 - Diesel Spray on Top
Overhead Temperature (°C)
0
200
400
600
800
Mockup Fwd Stbd
Mockup Fwd Port
Mockup Aft Stbd
Mockup Aft Port
0
50
100
150
200
250
300
350
Time (sec)

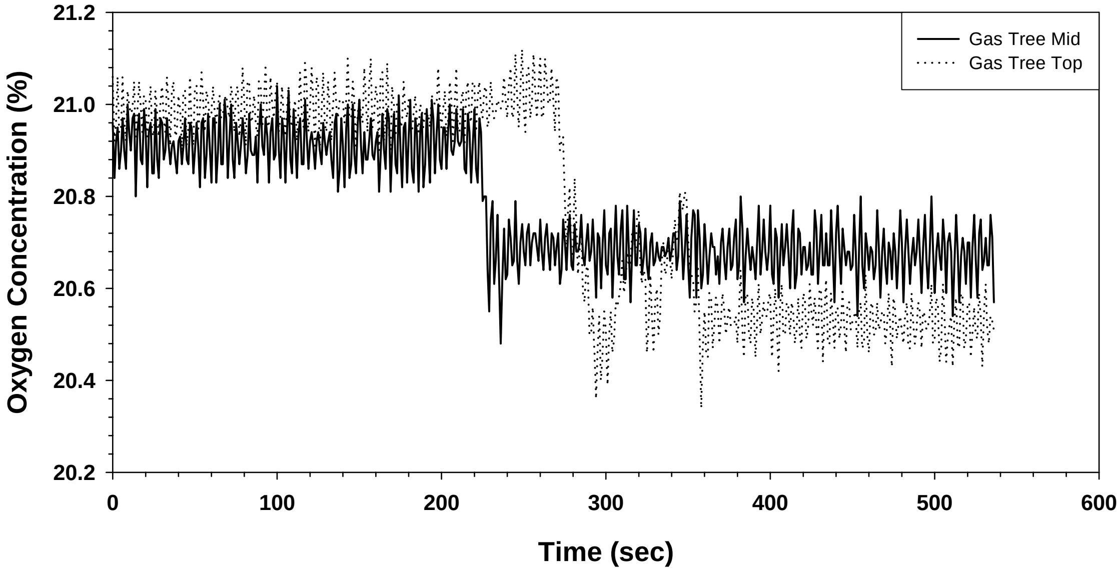
Buckeye Test 9 - Heptane Spray on Top



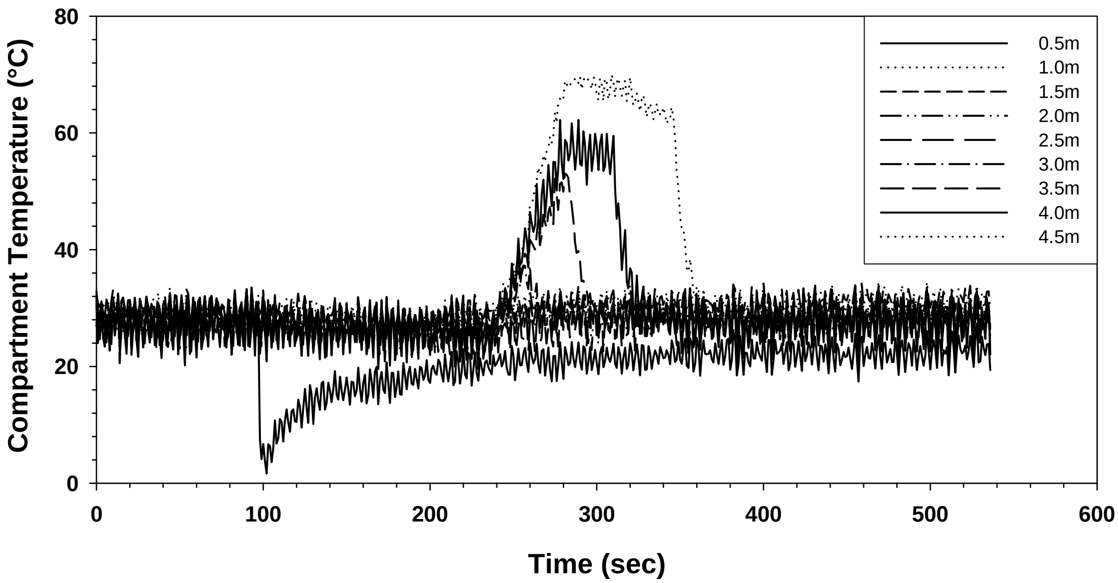
Buckeye Test 9 - Heptane Spray on Top



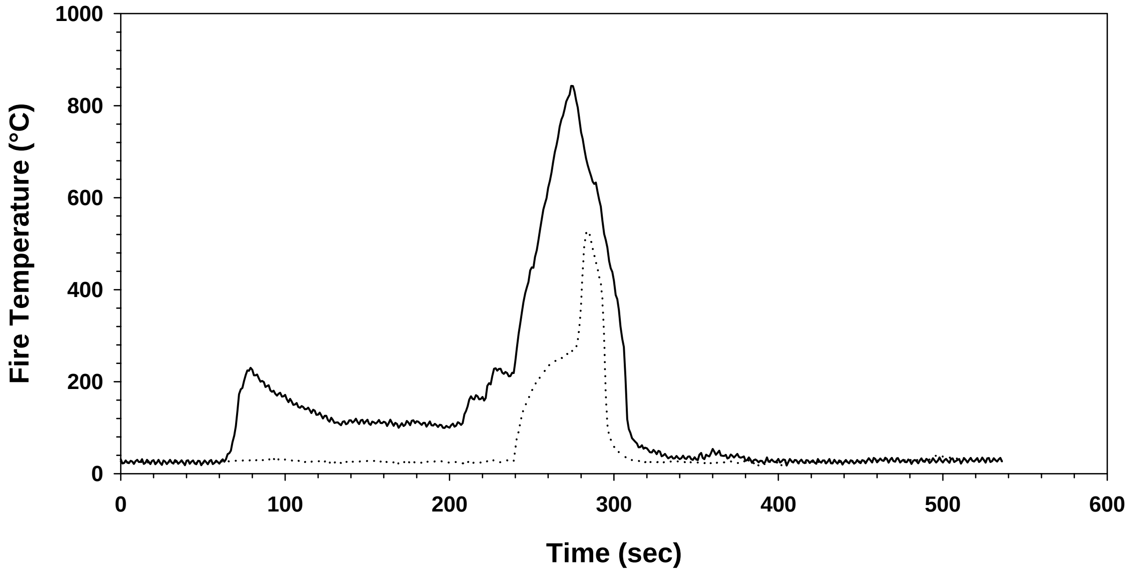
Buckeye Test 9 - Heptane Spray on Top



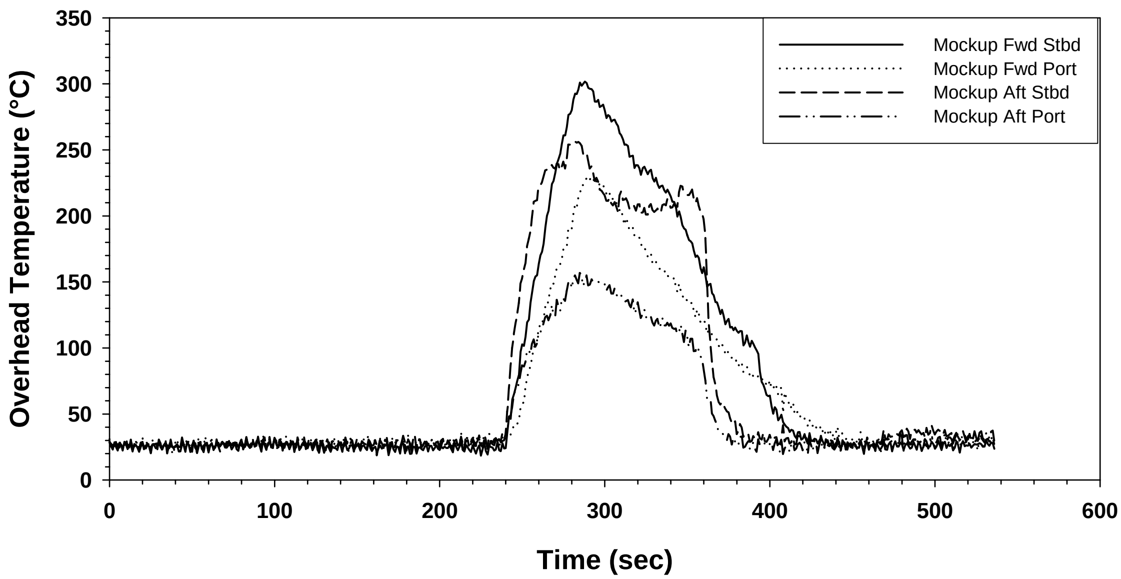
Buckeye Test 9 - Heptane Spray on Top



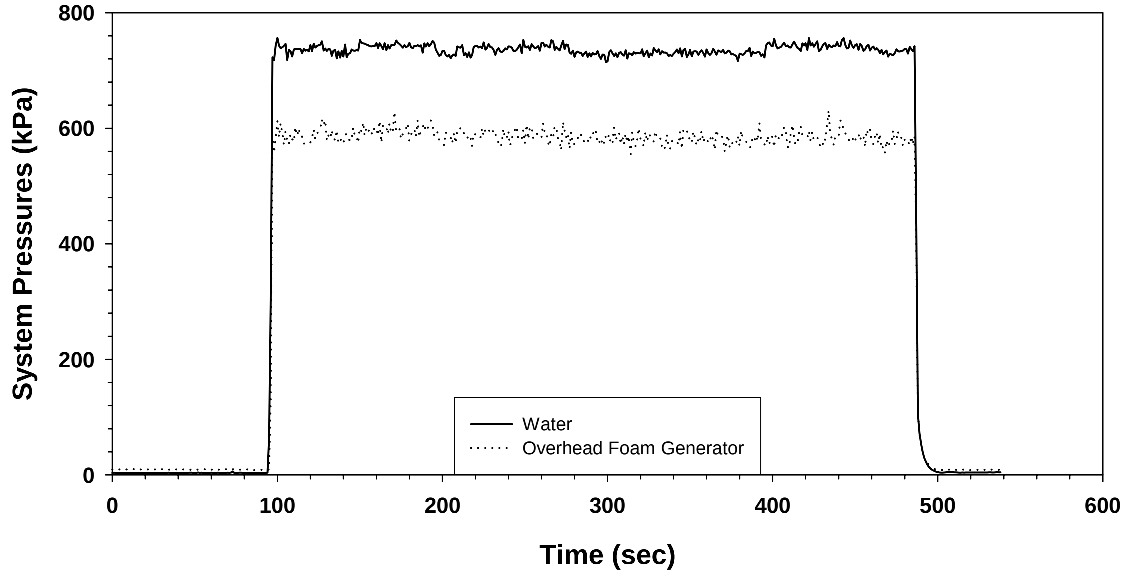
Buckeye Test 9 - Heptane Spray on Top



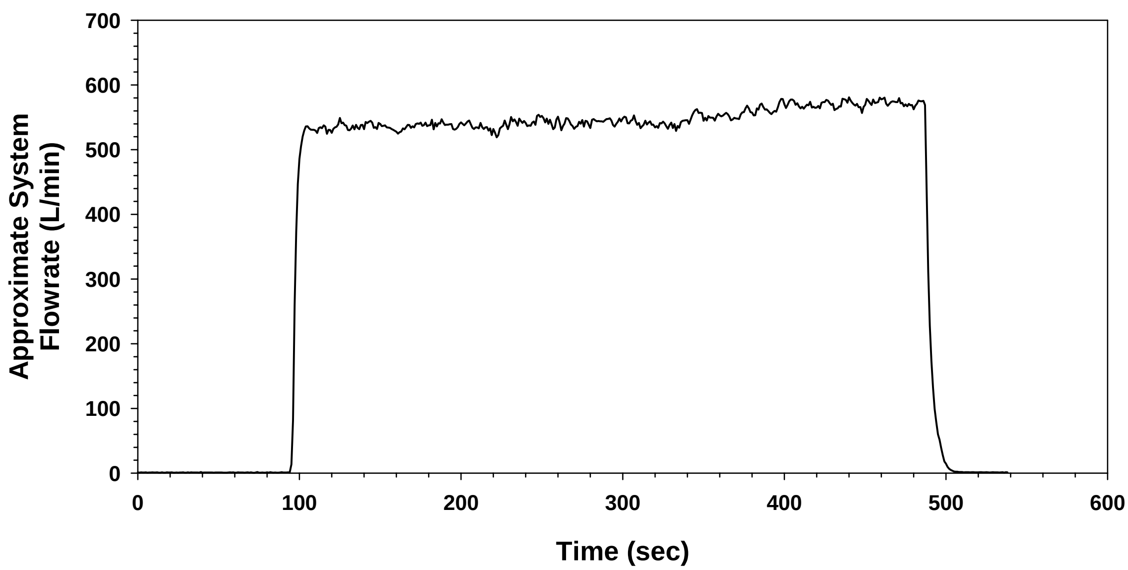
Buckeye Test 9 - Heptane Spray on Top



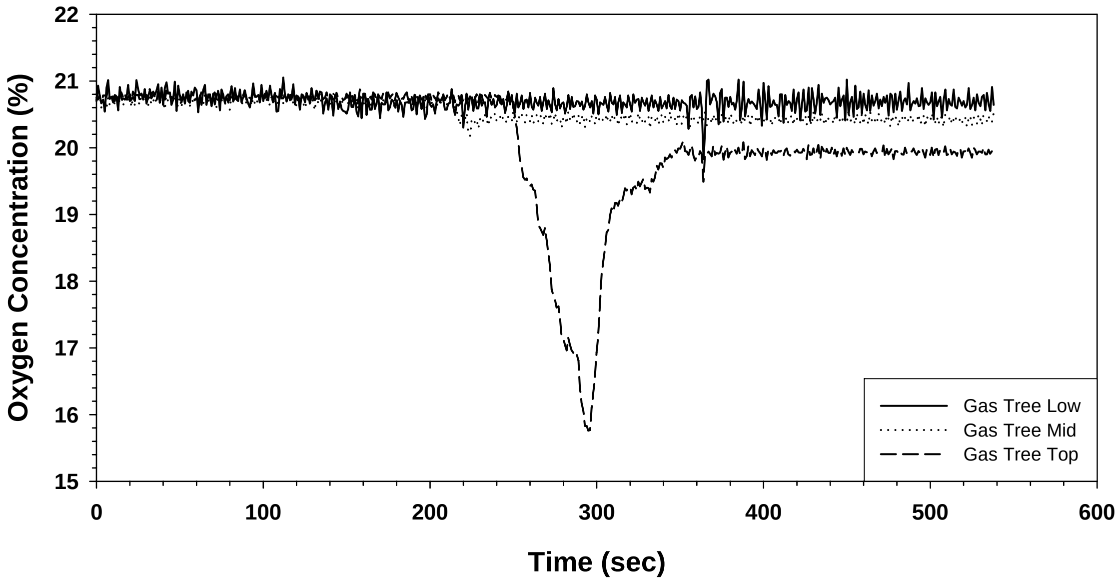
Buckeye Test 10 - Heptane Spray on Top



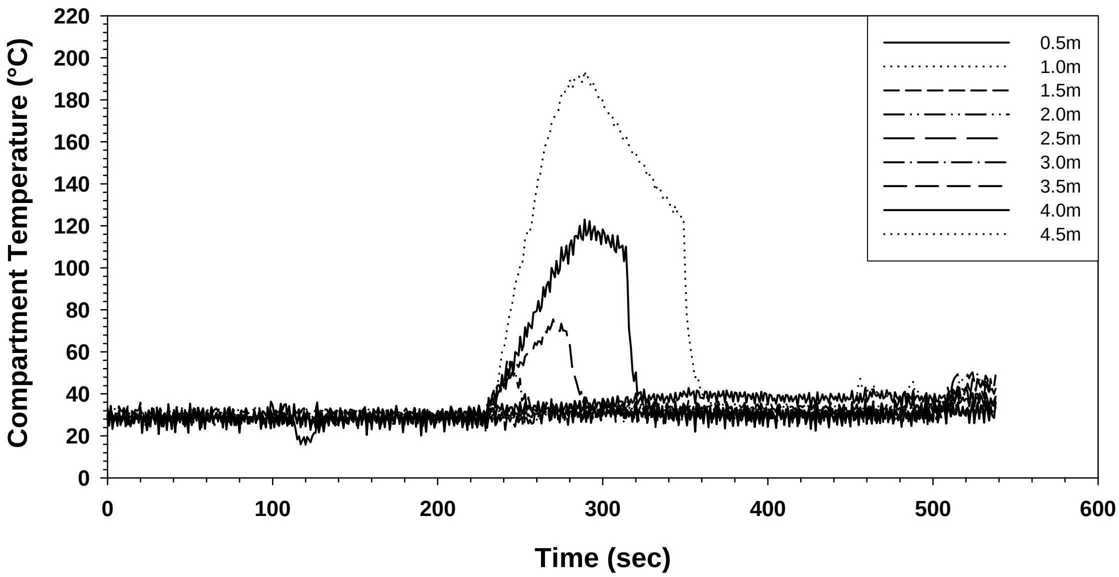
Buckeye Test 10 - Heptane Spray on Top



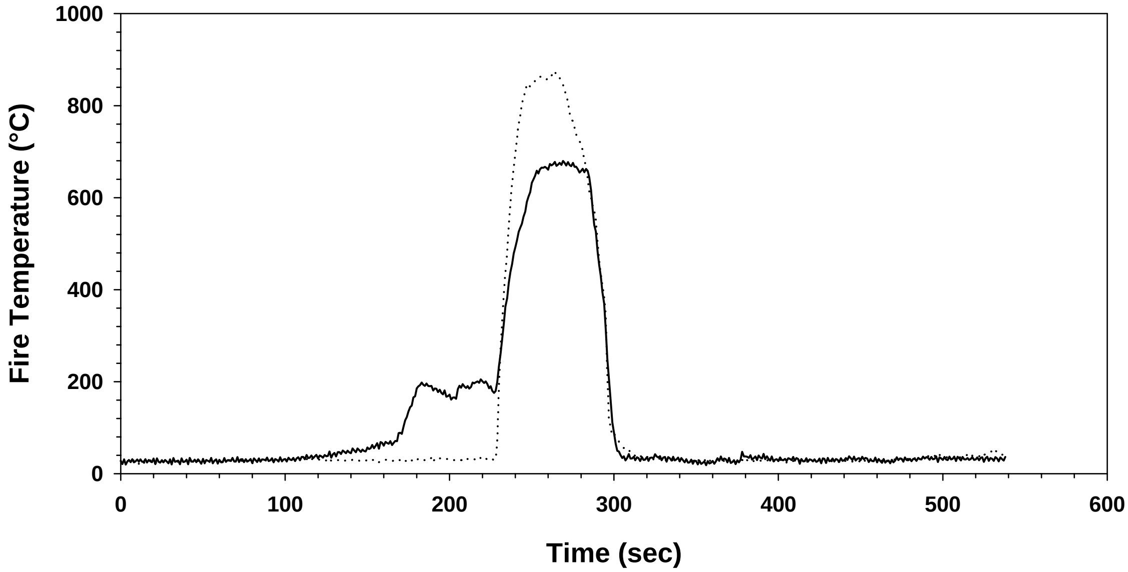
Buckeye Test 10 - Heptane Spray on Top



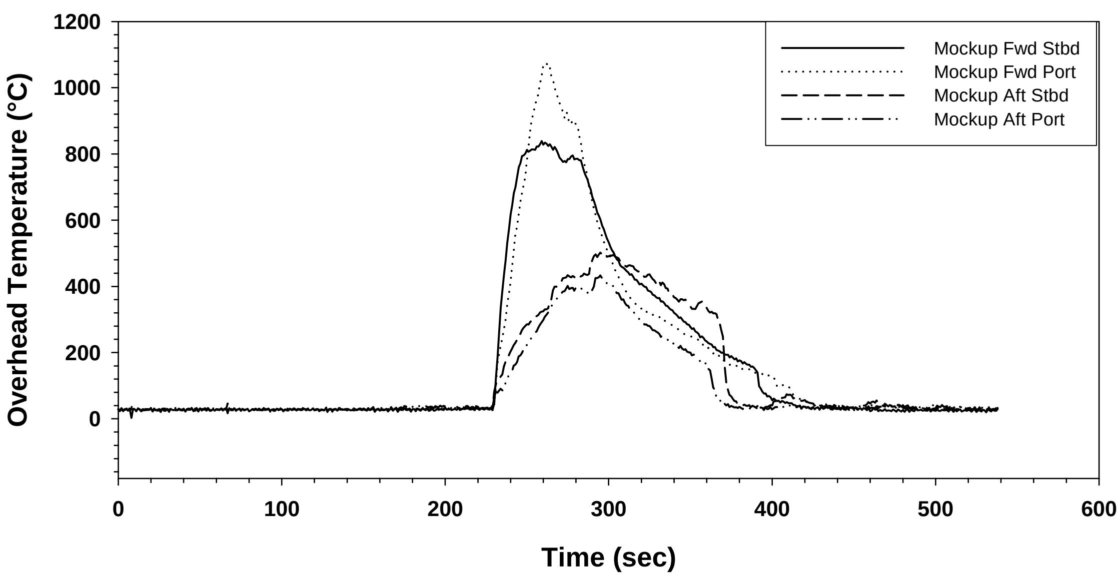
Buckeye Test 10 - Heptane Spray on Top



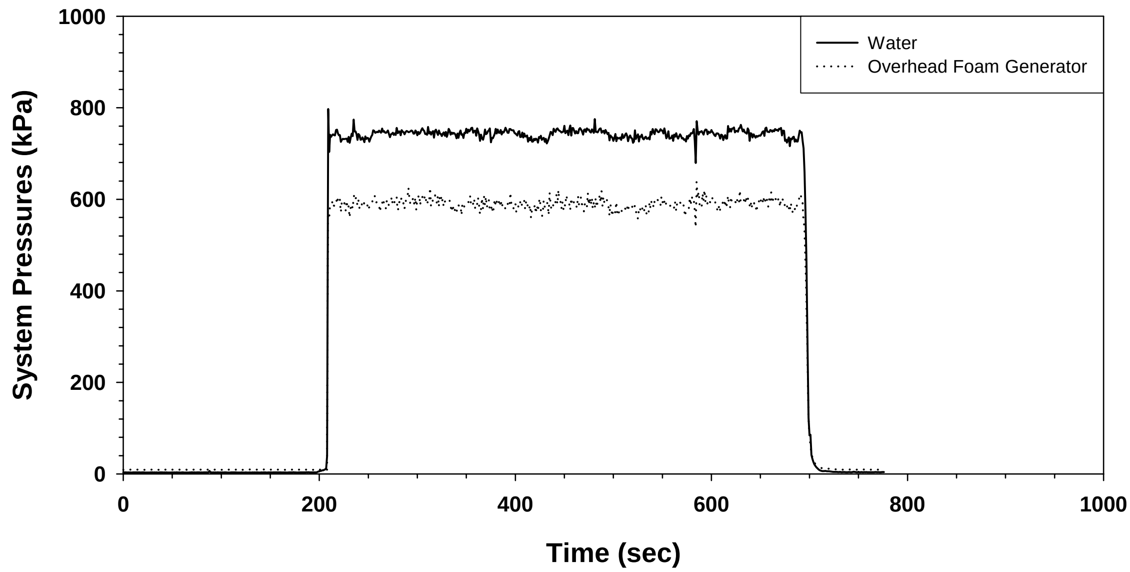
Buckeye Test 10 - Heptane Spray on Top



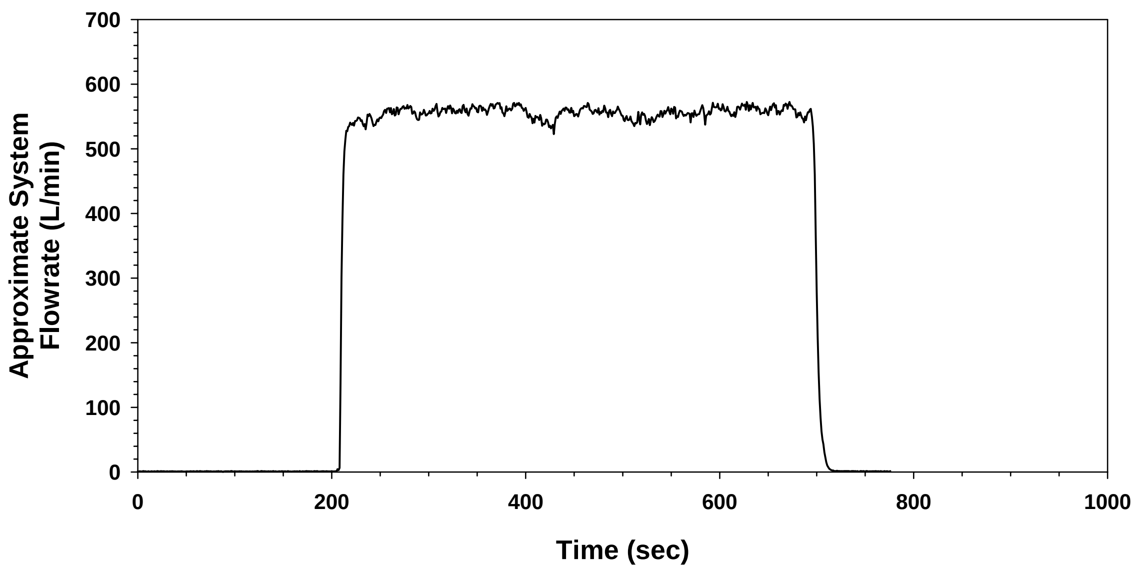
Buckeye Test 10 - Heptane Spray on Top



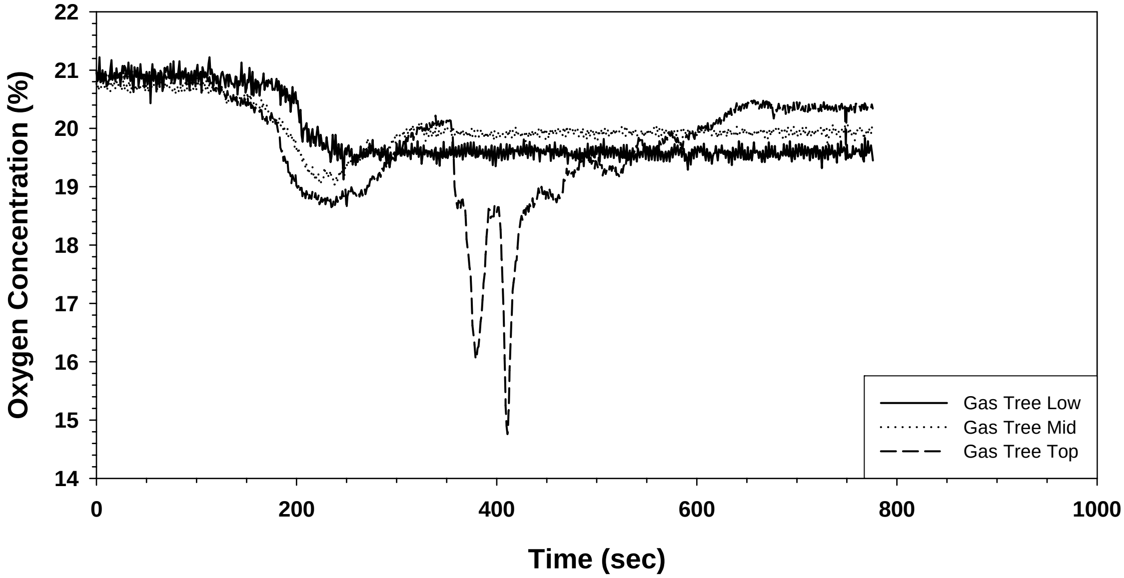
Buckeye Test 11 - Scenario 2



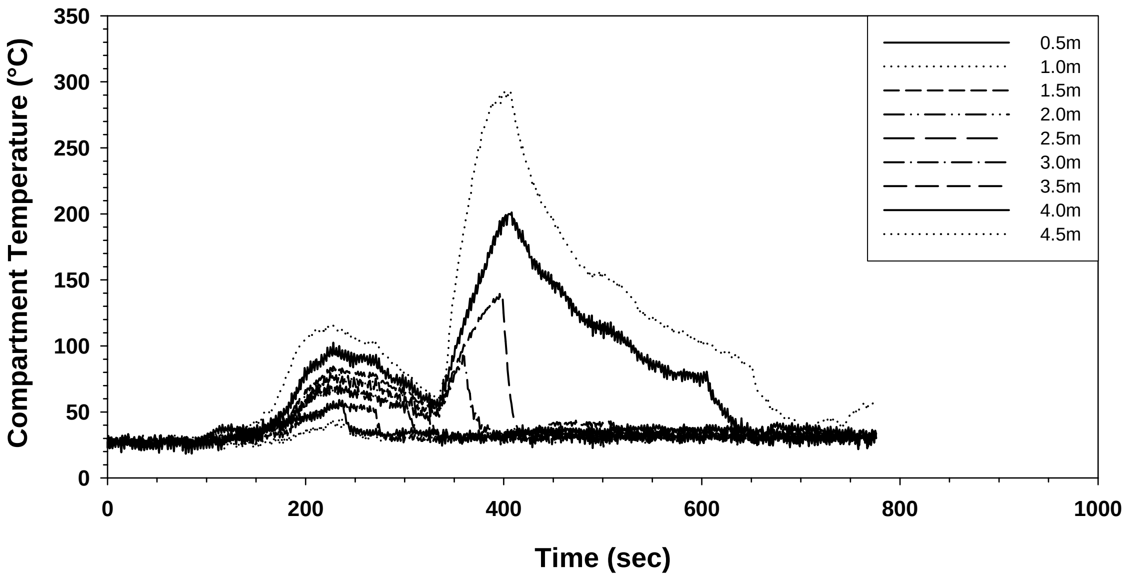
Buckeye Test 11 - Scenario 2



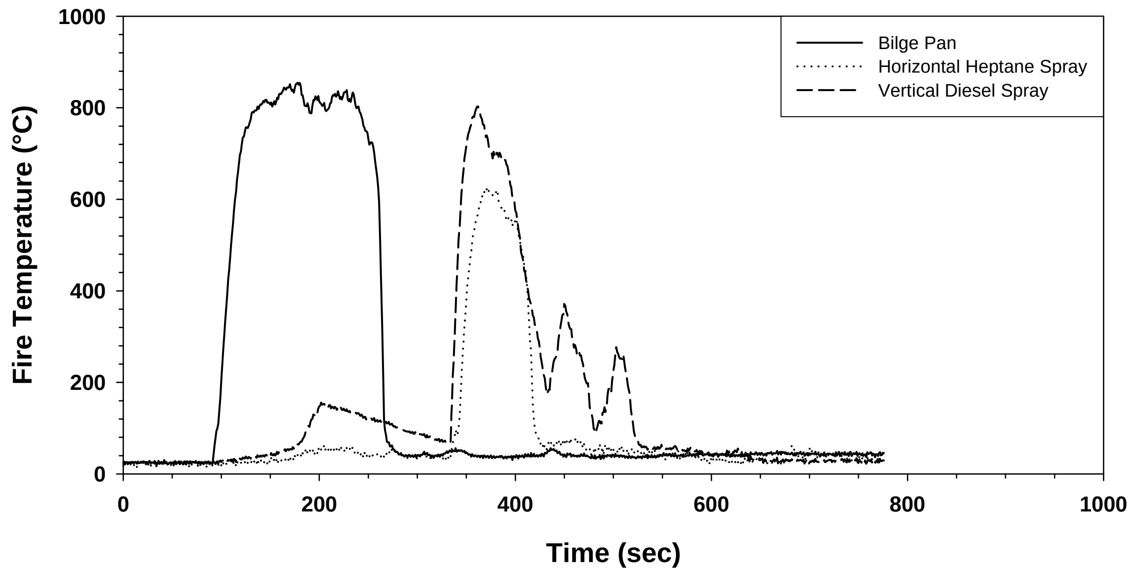
Buckeye Test 11 - Scenario 2



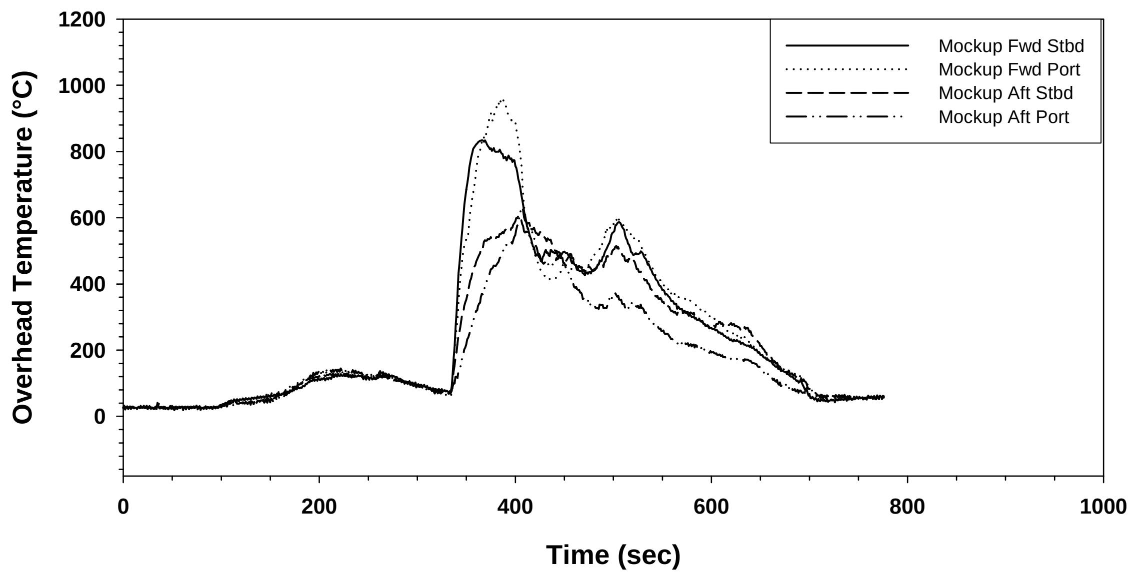
Buckeye Test 11 - Scenario 2



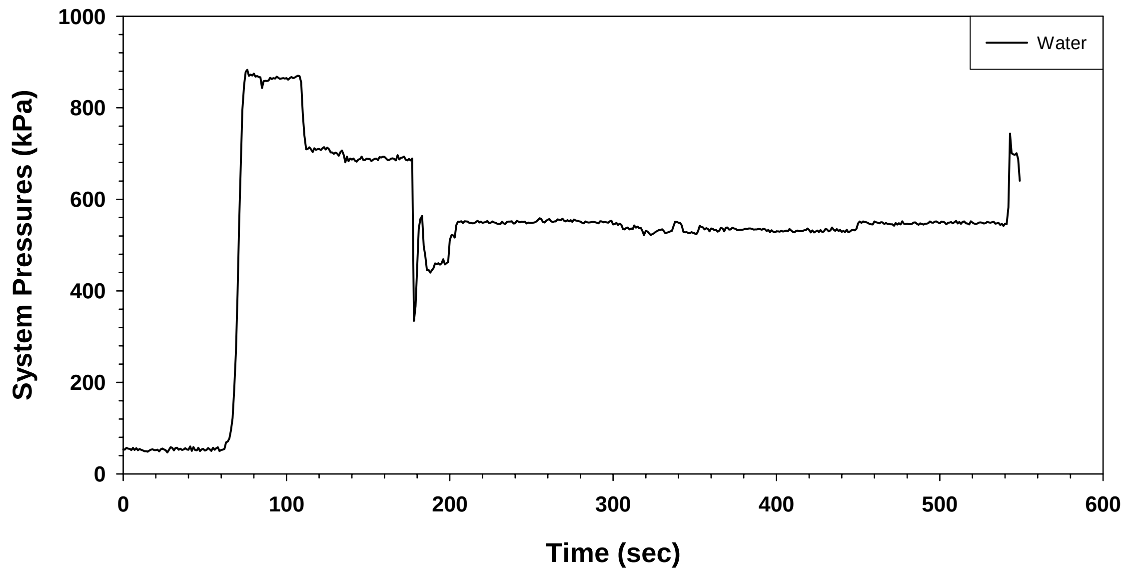
Buckeye Test 11 - Scenario 2



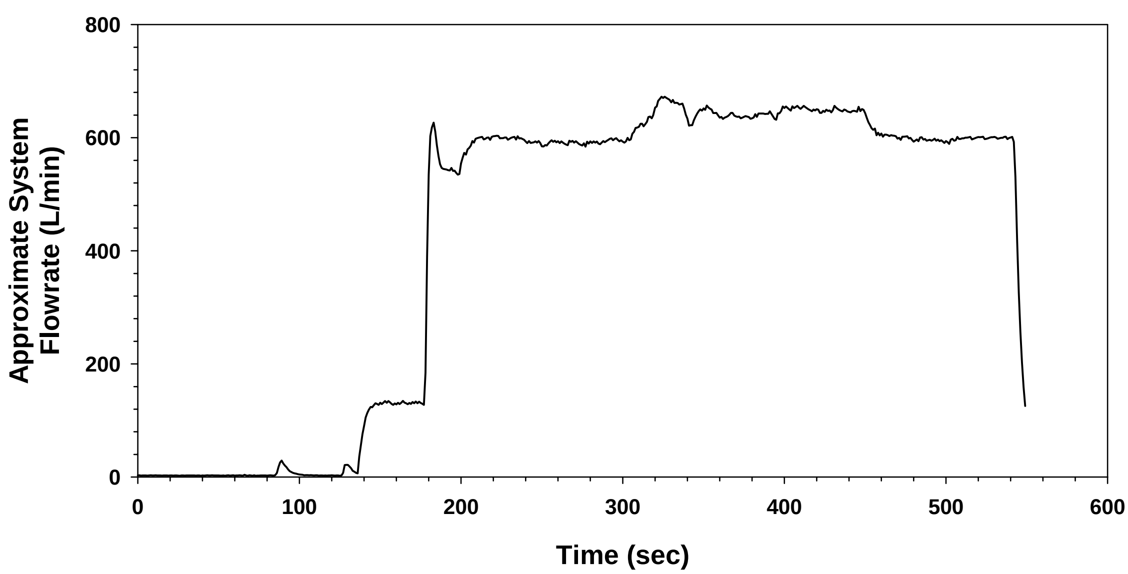
Buckeye Test 11 - Scenario 2

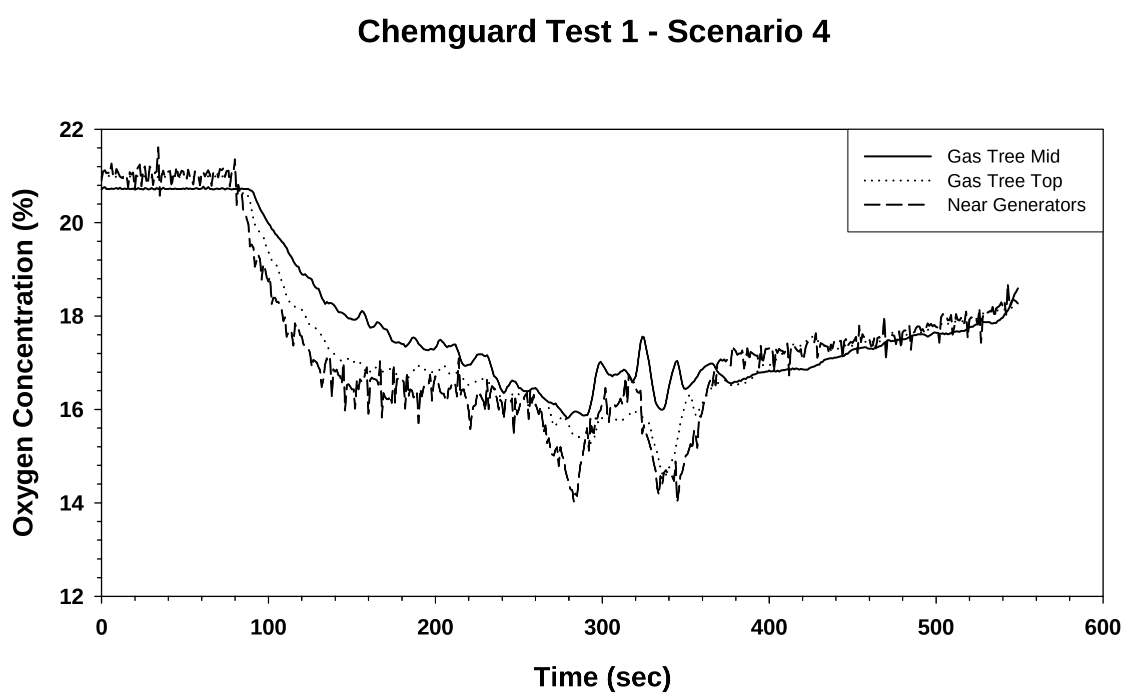


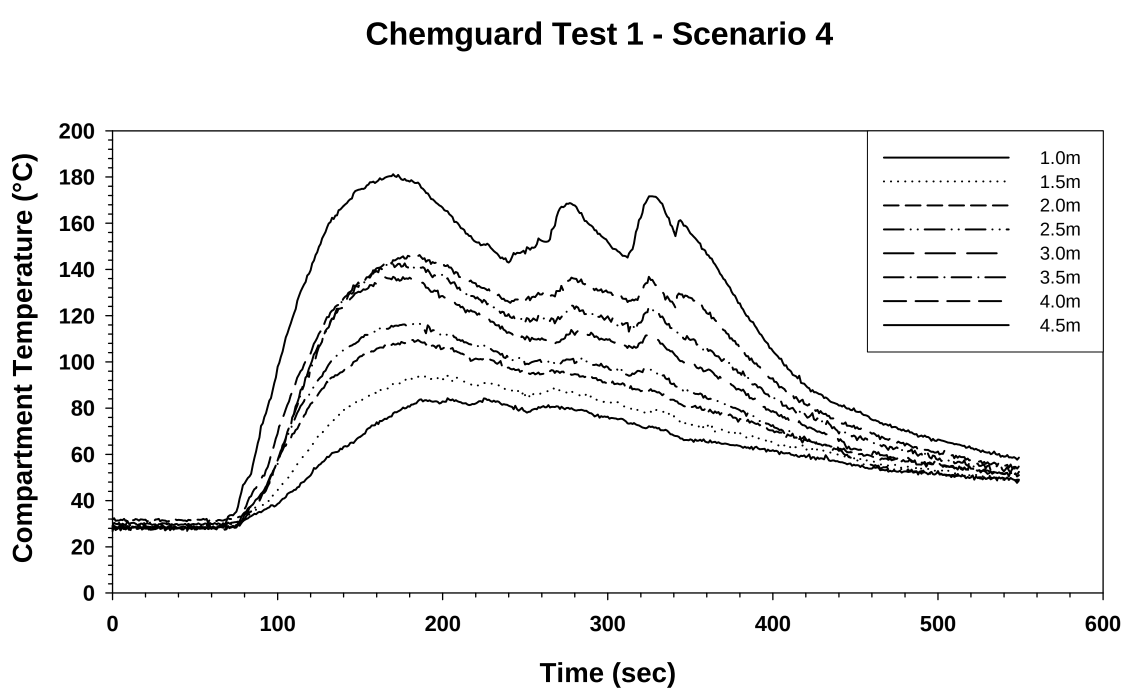
Chemguard Test 1 - Scenario 4



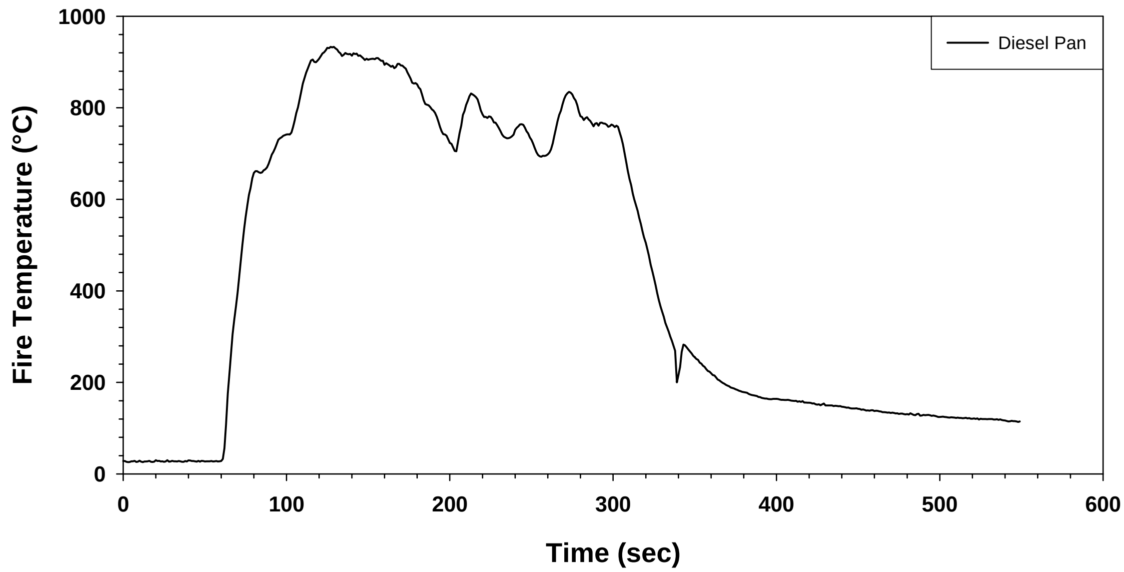
Chemguard Test 1 - Scenario 4



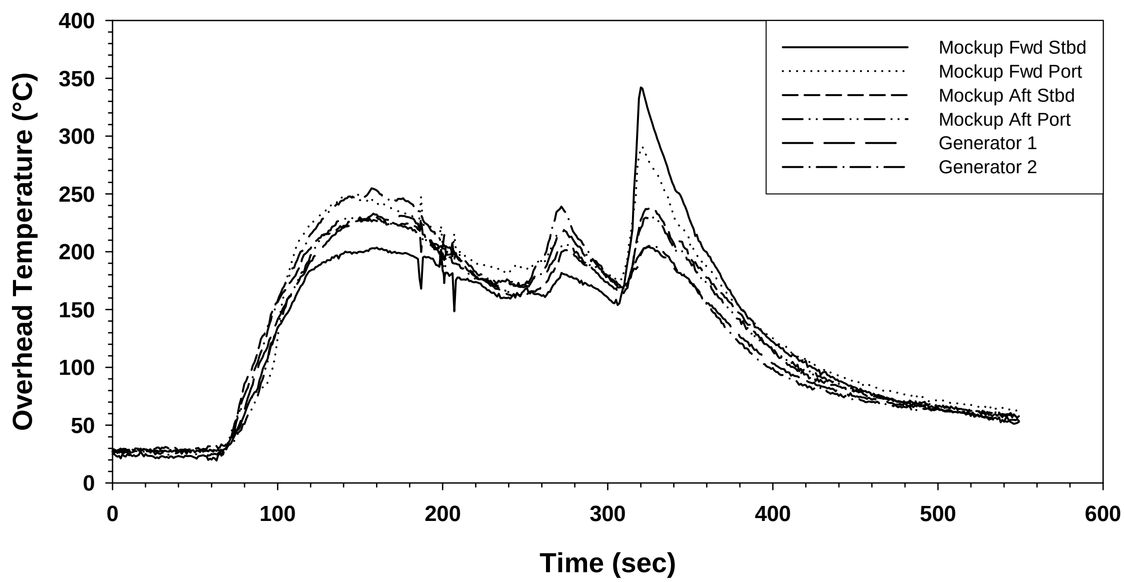

Chemguard Test 1 - Scenario 4
Oxygen Concentration (%)
Time (sec)
Gas Tree Mid
Gas Tree Top
Near Generators
22
20
18
16
14
12
0
100
200
300
400
500
600


Chemguard Test 1 - Scenario 4
Compartment Temperature (°C)
Time (sec)
1.0m
1.5m
2.0m
2.5m
3.0m
3.5m
4.0m
4.5m
200
180
160
140
120
100
80
60
40
20
0
0
100
200
300
400
500
600

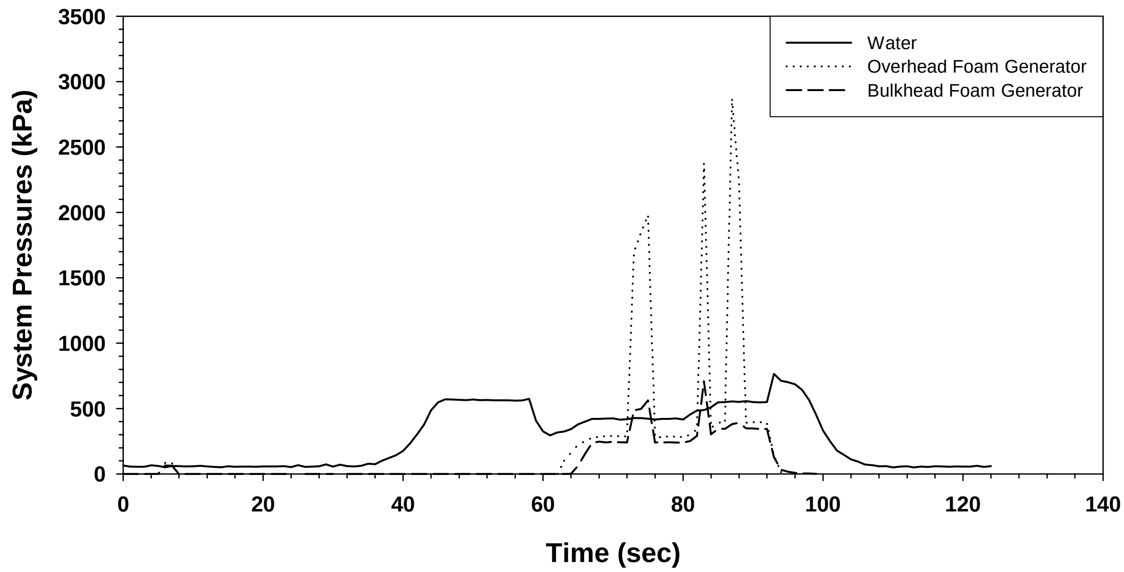
Chemguard Test 1 - Scenario 4



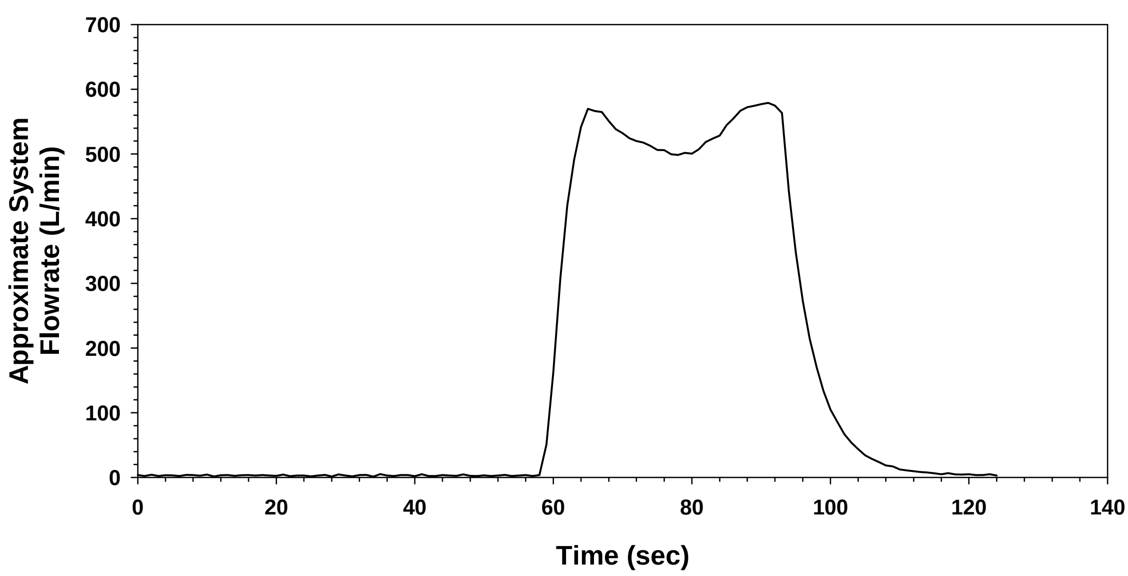
Chemguard Test 1 - Scenario 4



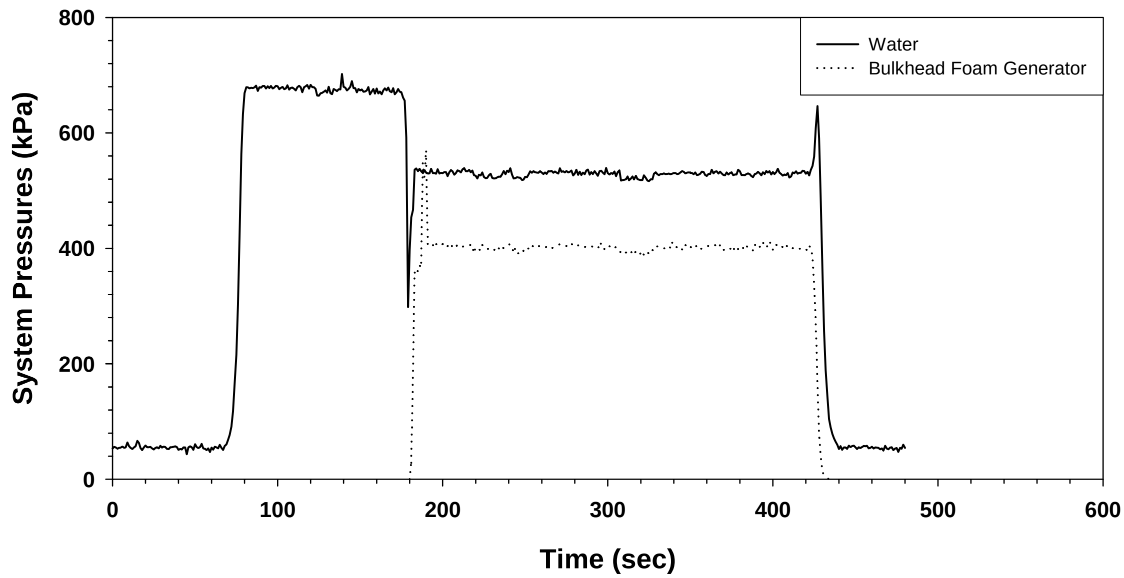
Chemguard Test 2 - Cold Discharge



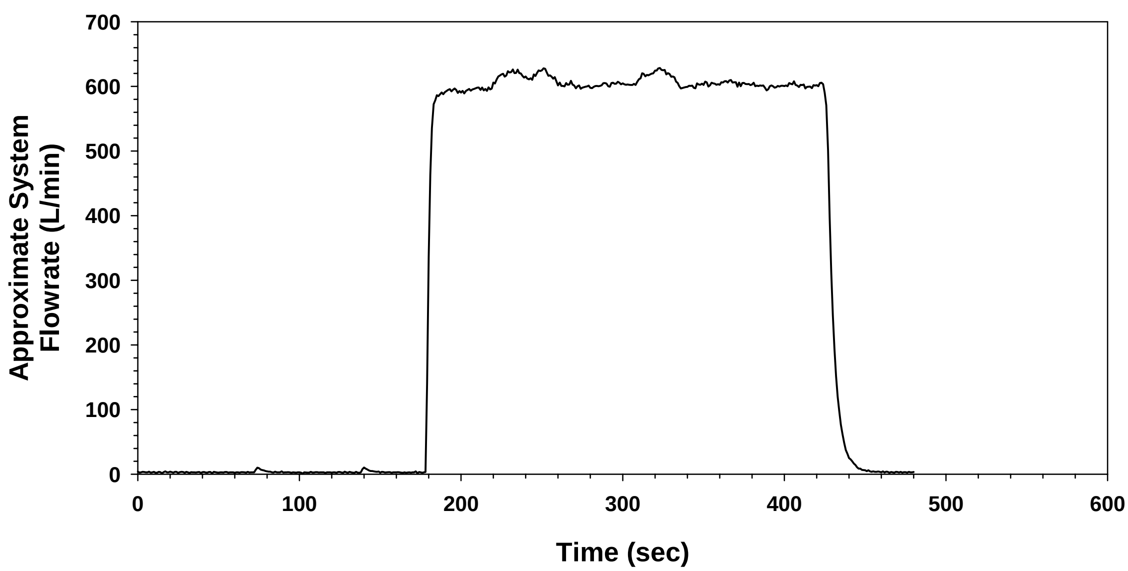
Chemguard Test 2 - Cold Discharge

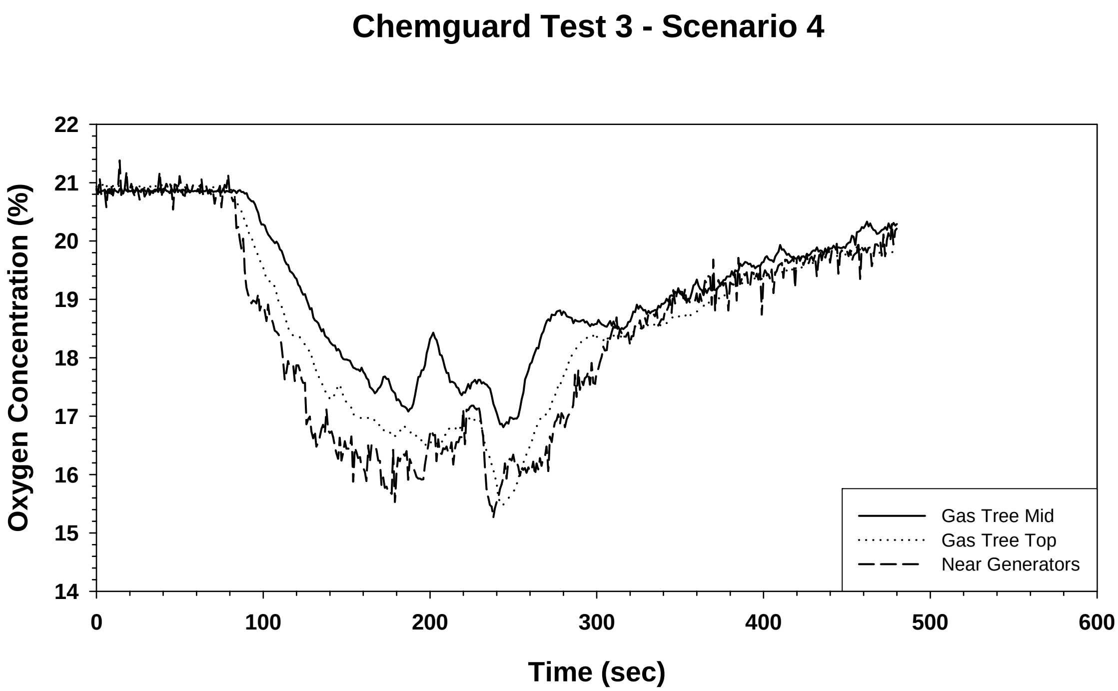


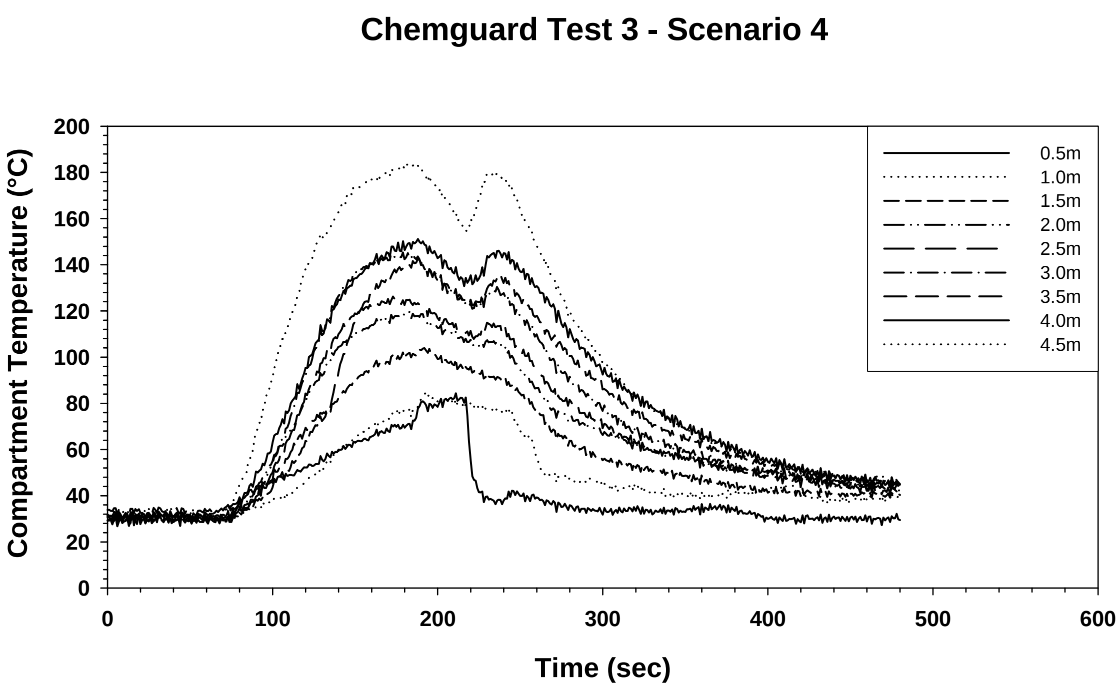
Chemguard Test 3 - Scenario 4



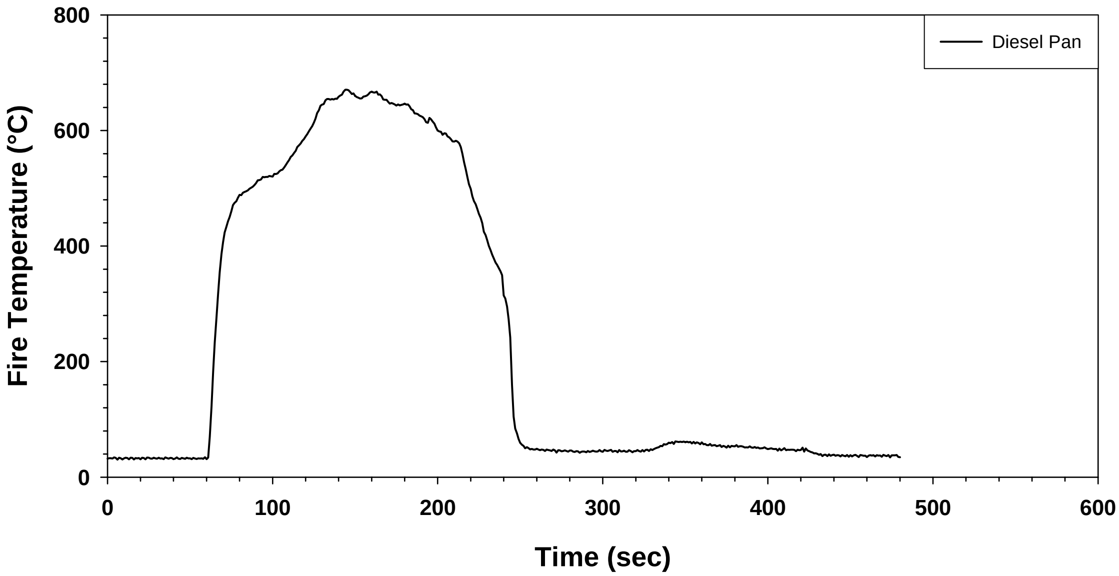
Chemguard Test 3 - Scenario 4



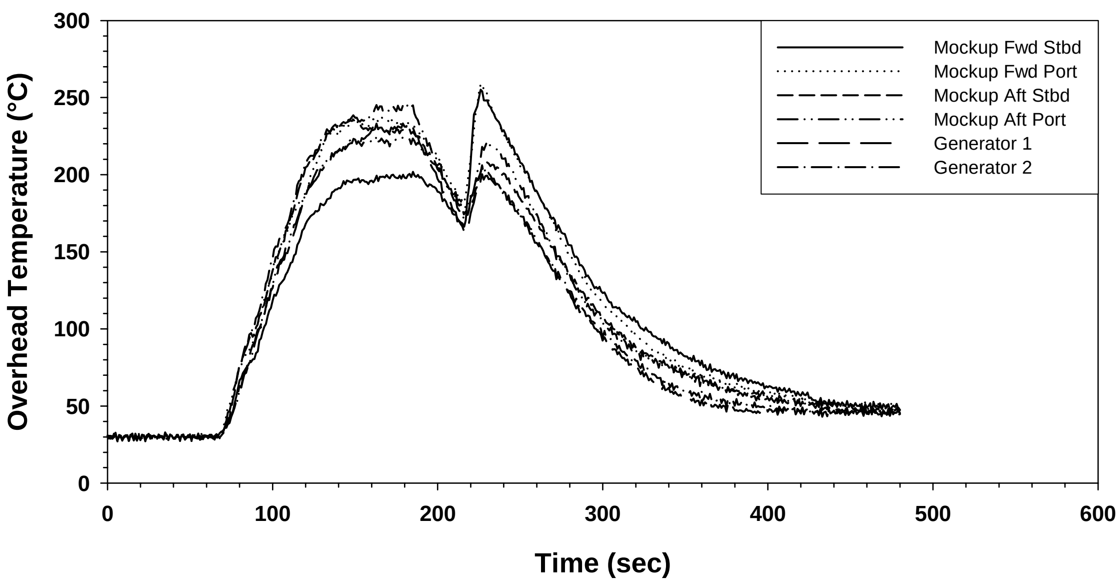

Chemguard Test 3 - Scenario 4
Oxygen Concentration (%)
Time (sec)
Gas Tree Mid
Gas Tree Top
Near Generators


Chemguard Test 3 - Scenario 4
Compartment Temperature (°C)
Time (sec)
0.5m
1.0m
1.5m
2.0m
2.5m
3.0m
3.5m
4.0m
4.5m

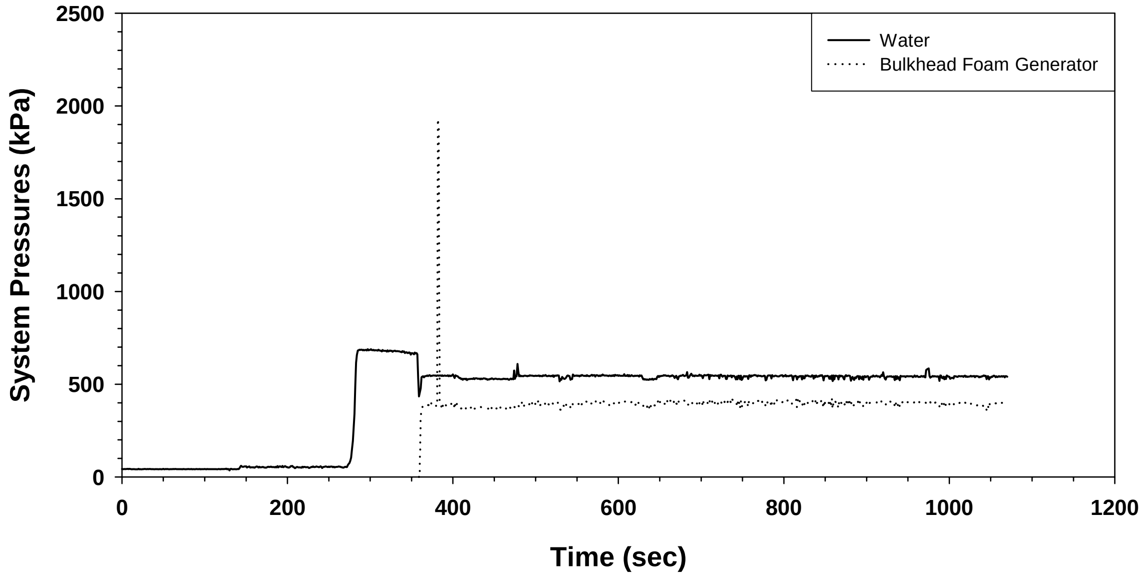
Chemguard Test 3 - Scenario 4



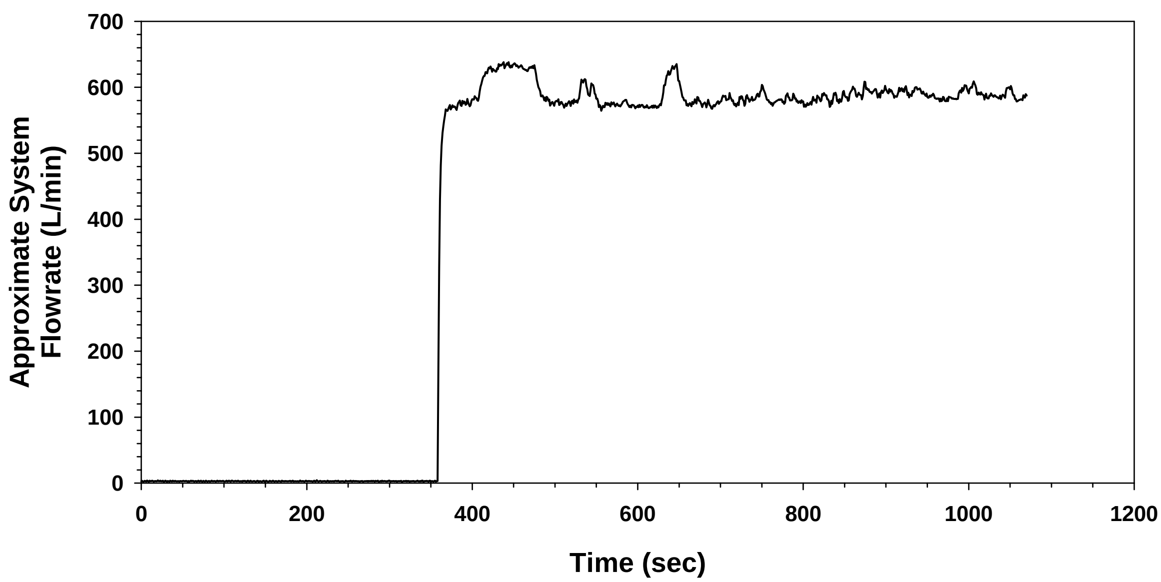
Chemguard Test 3 - Scenario 4



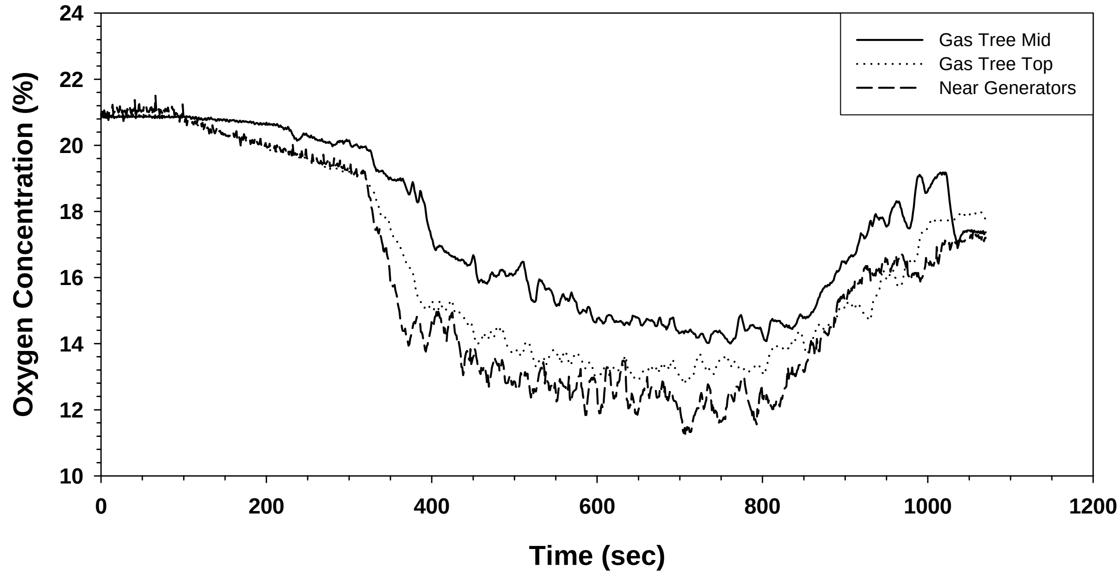
Chemguard Test 4 - Scenario 3



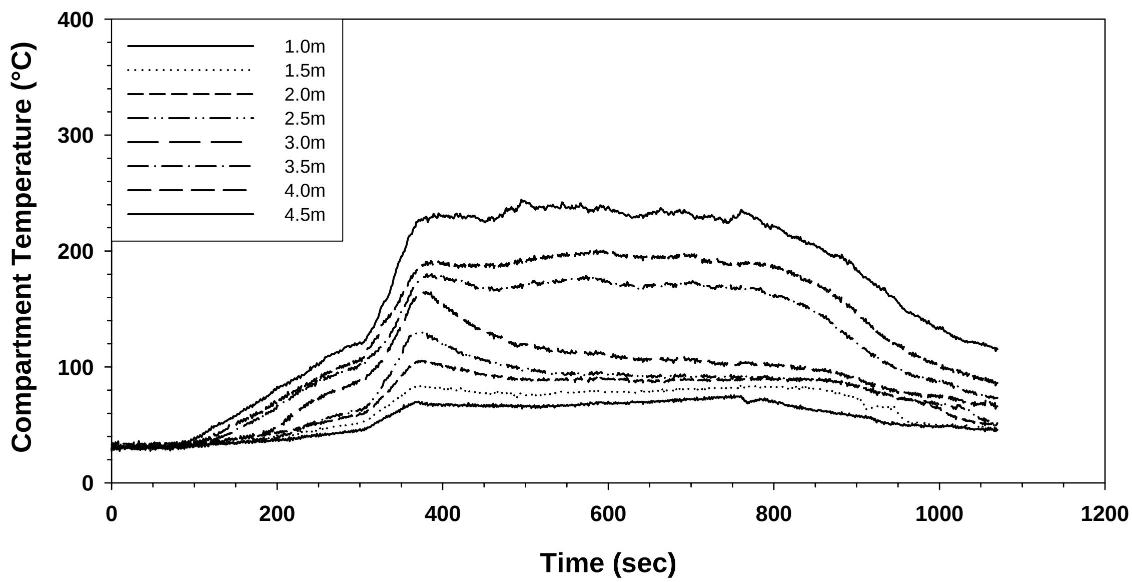
Chemguard Test 4 - Scenario 3



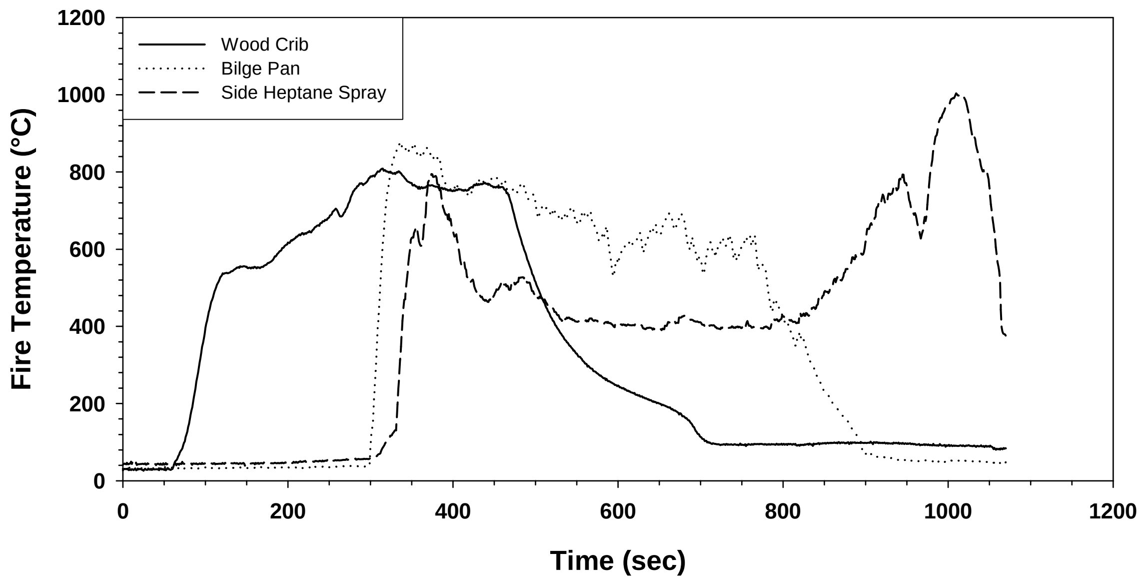
Chemguard Test 4 - Scenario 3



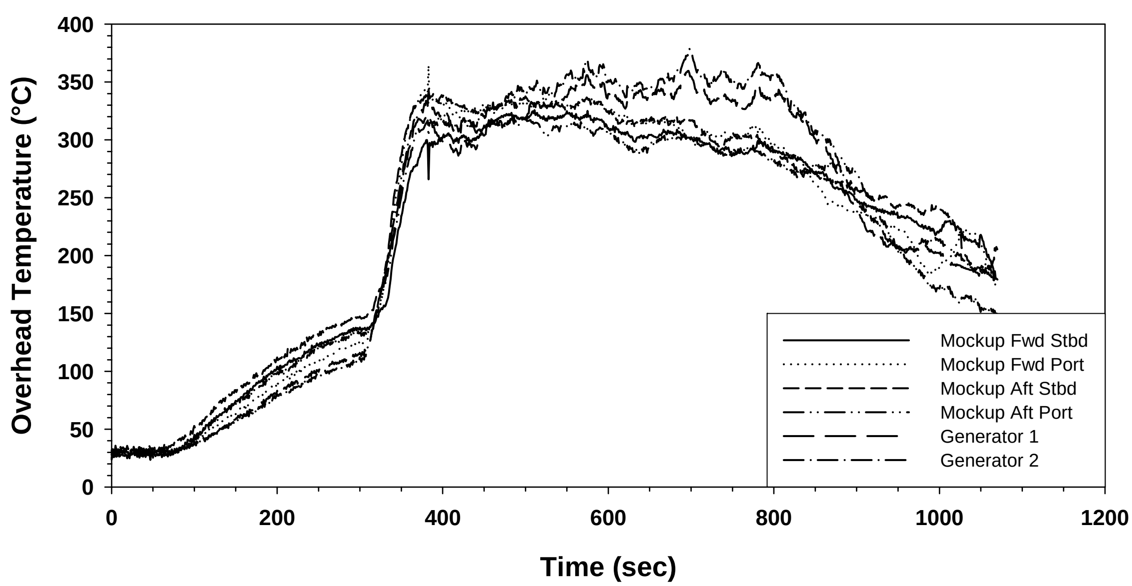
Chemguard Test 4 - Scenario 3



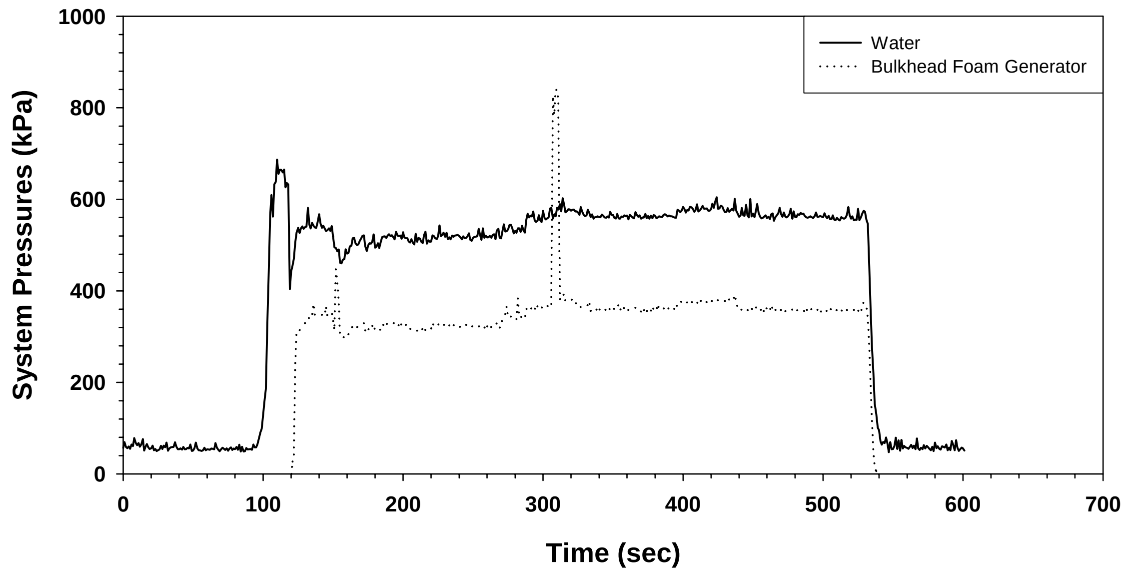
Chemguard Test 4 - Scenario 3



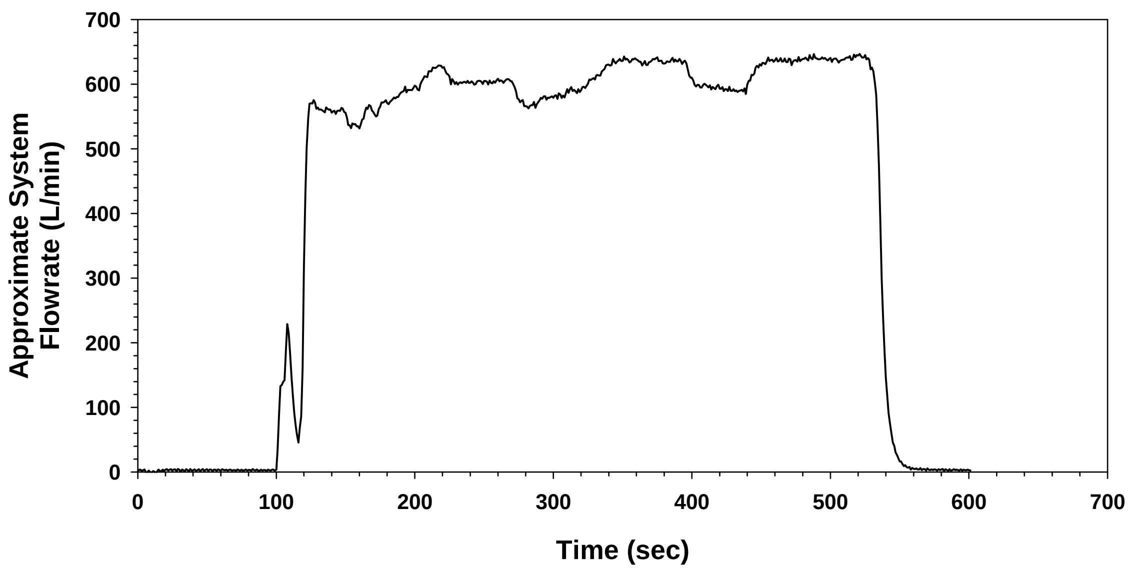
Chemguard Test 4 - Scenario 3

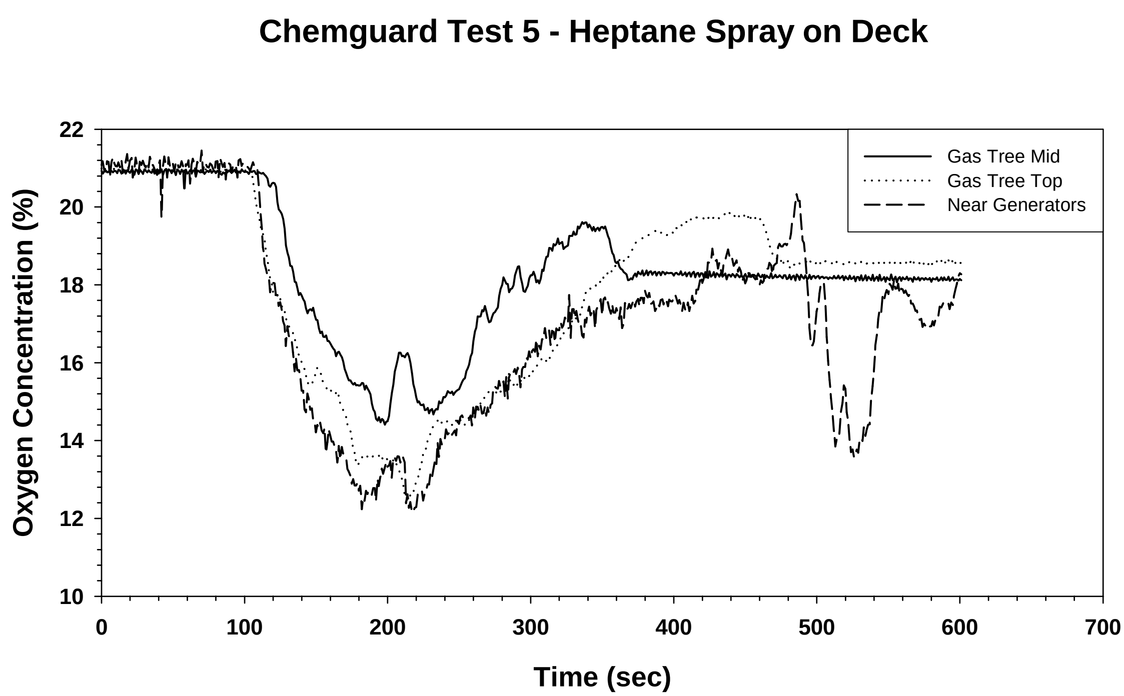


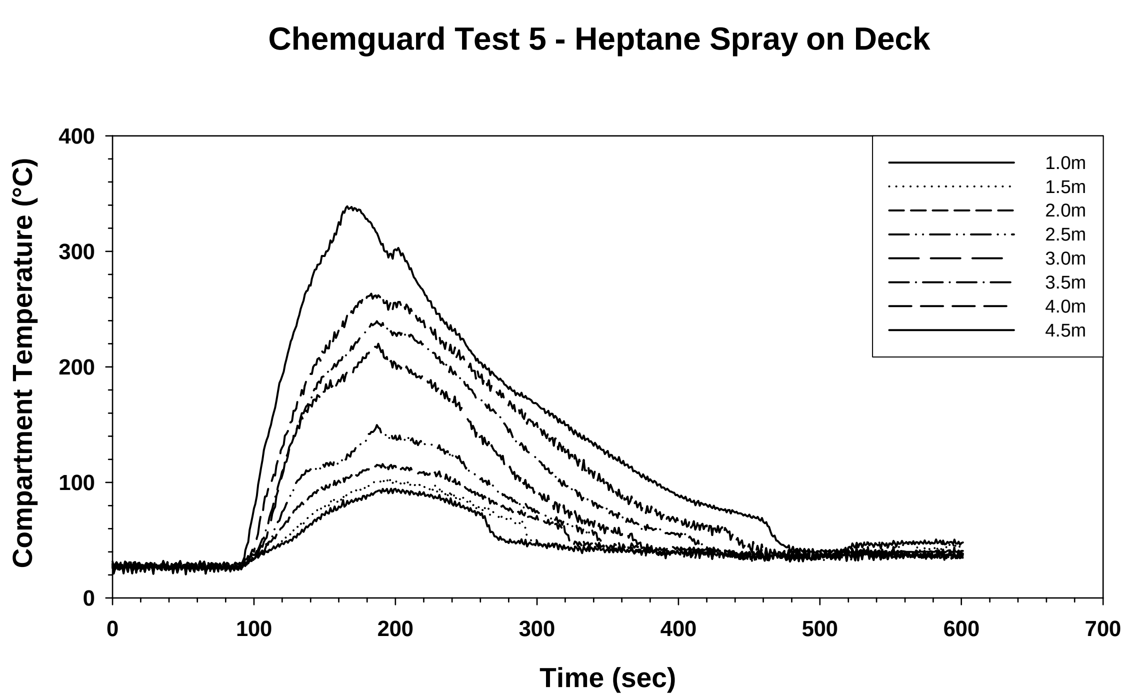
Chemguard Test 5 - Heptane Spray on Deck

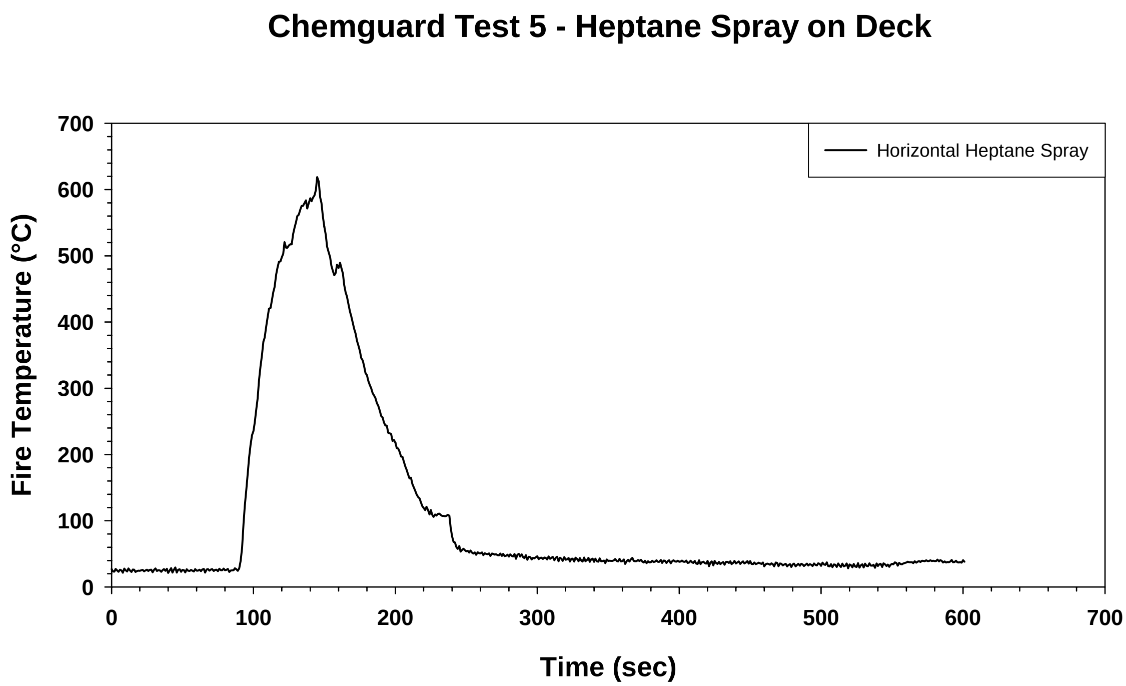


Chemguard Test 5 - Heptane Spray on Deck

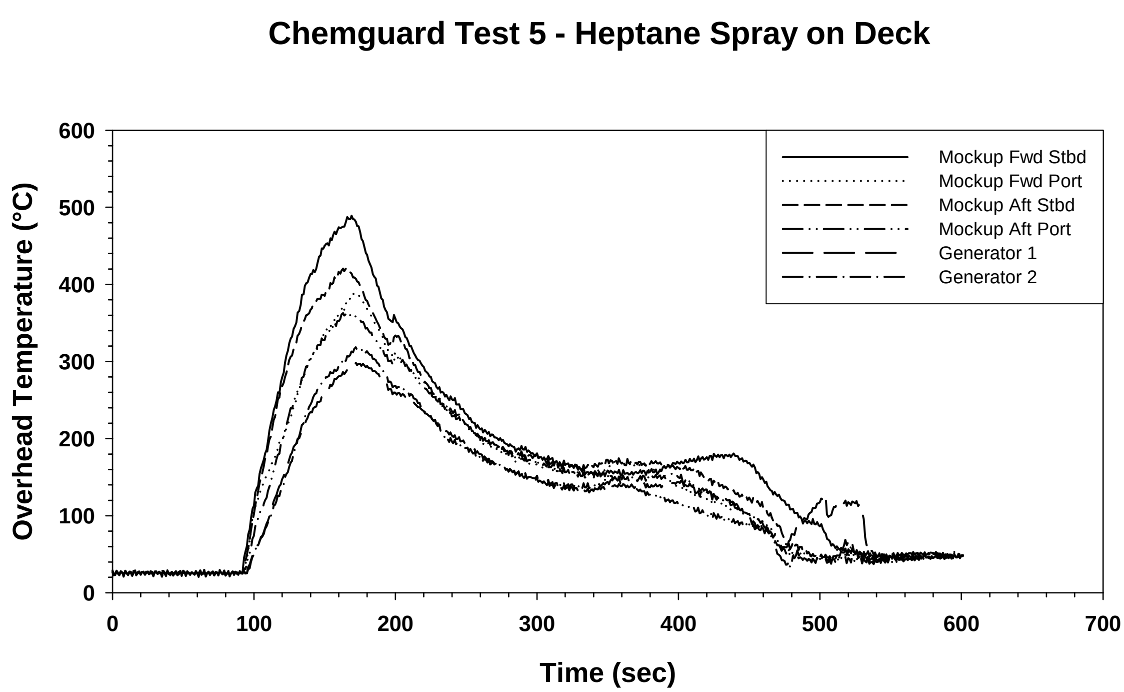



Chemguard Test 5 - Heptane Spray on Deck
Oxygen Concentration (%)
Time (sec)
Gas Tree Mid
Gas Tree Top
Near Generators
22
20
18
16
14
12
10
0
100
200
300
400
500
600
700


Chemguard Test 5 - Heptane Spray on Deck
Compartment Temperature (°C)
Time (sec)
1.0m
1.5m
2.0m
2.5m
3.0m
3.5m
4.0m
4.5m
400
300
200
100
0
0
100
200
300
400
500
600
700

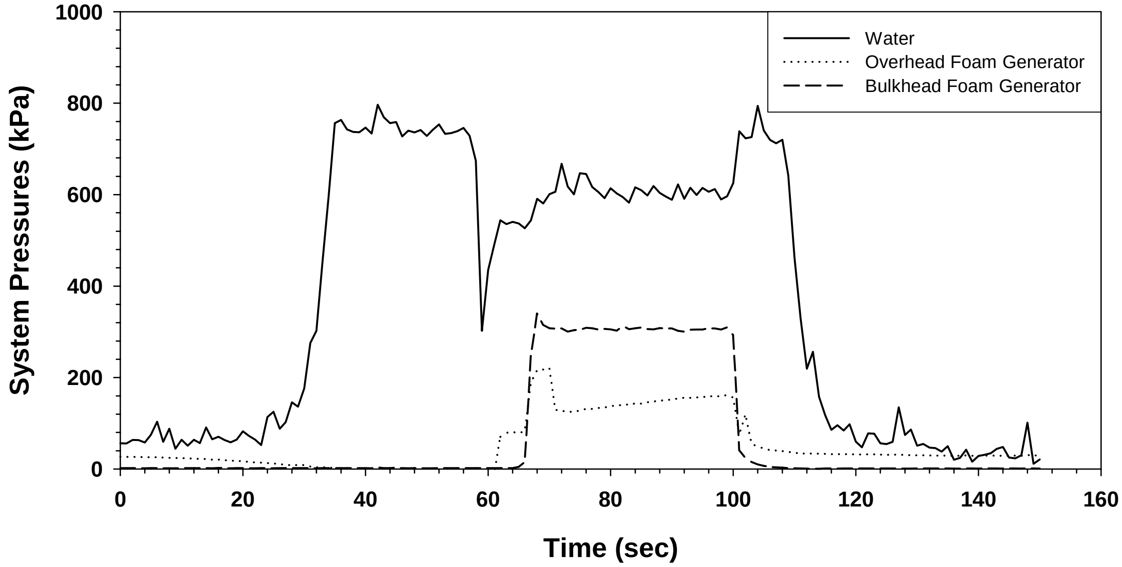


Chemguard Test 5 - Heptane Spray on Deck
Horizontal Heptane Spray
Fire Temperature (°C)
0
100
200
300
400
500
600
700
Time (sec)

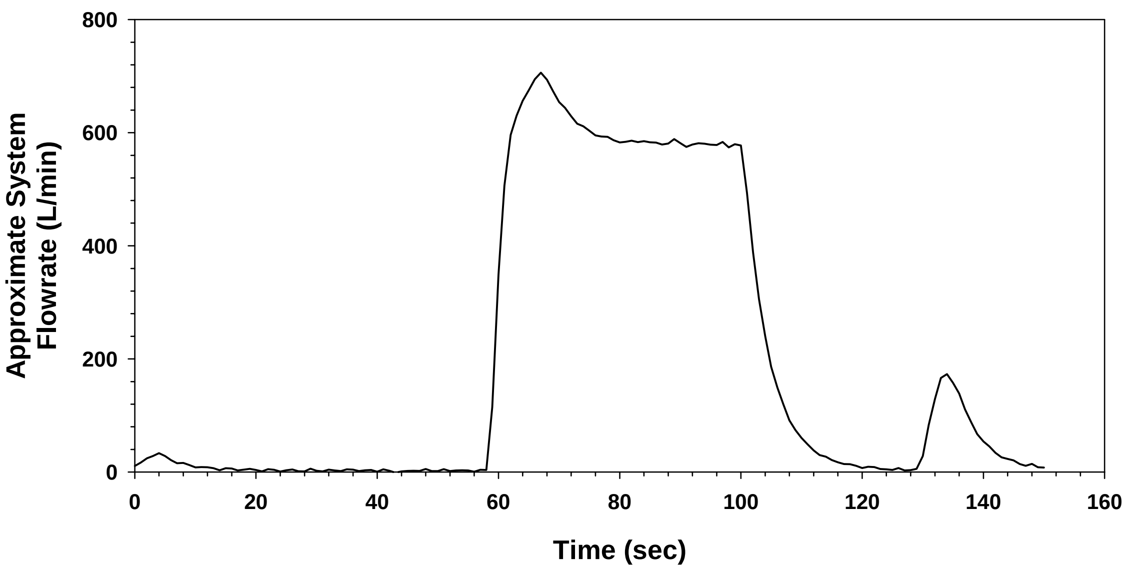


Chemguard Test 5 - Heptane Spray on Deck
Mockup Fwd Stbd
Mockup Fwd Port
Mockup Aft Stbd
Mockup Aft Port
Generator 1
Generator 2
Overhead Temperature (°C)
0
100
200
300
400
500
600
700
Time (sec)

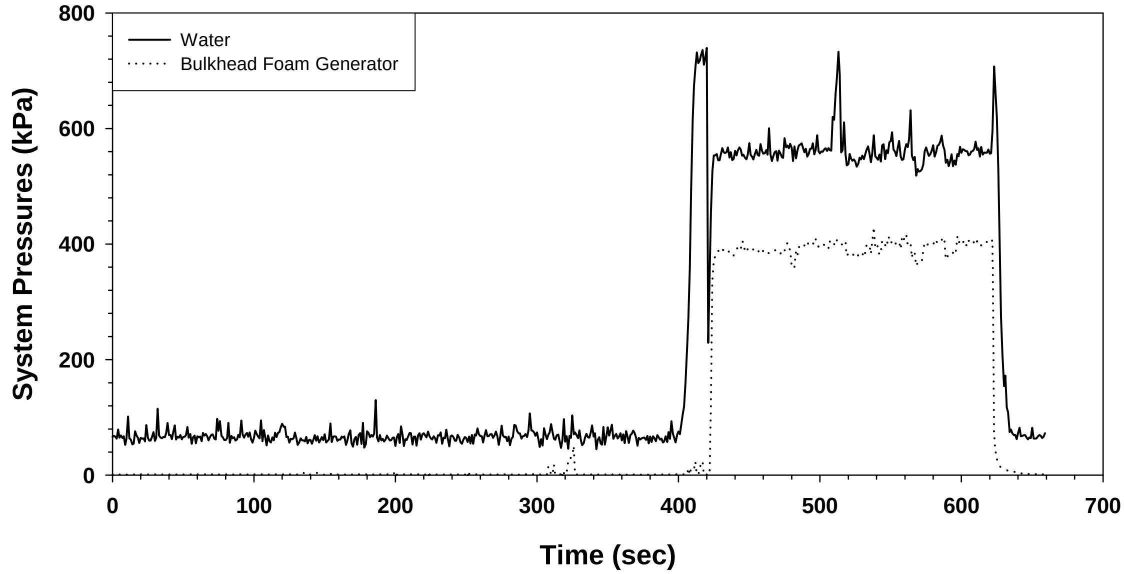
Chemguard Test 6 - Cold Discharge



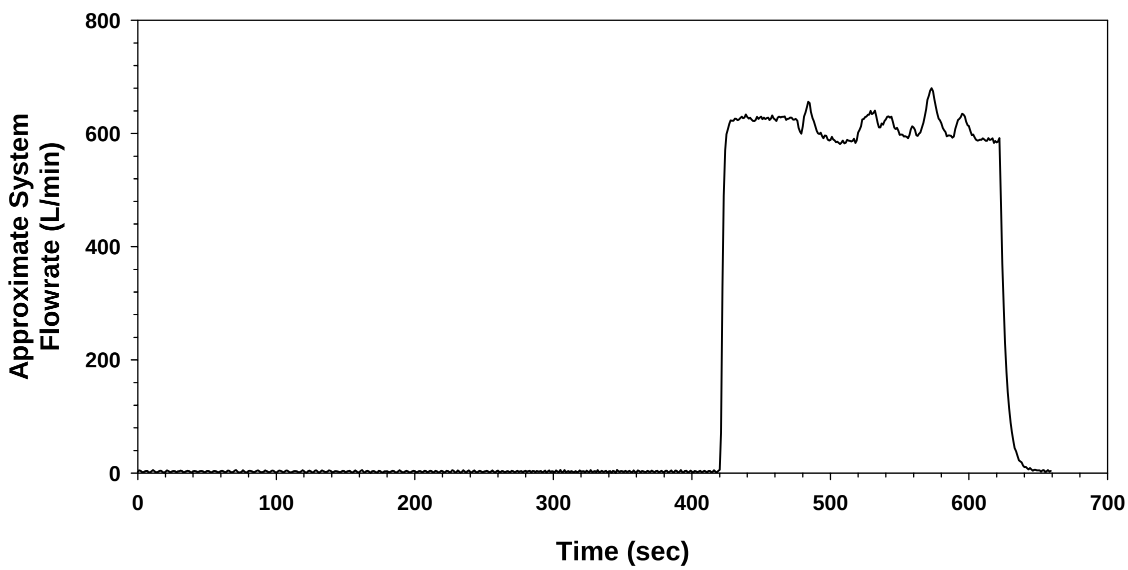
Chemguard Test 6 - Cold Discharge



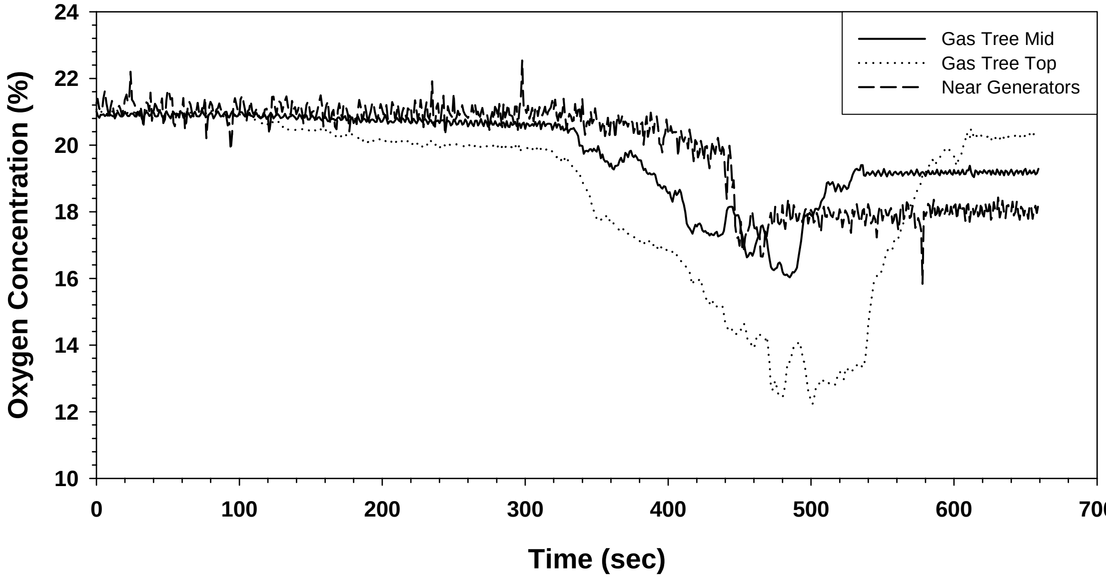
Chemguard Test 7 - Scenario 3



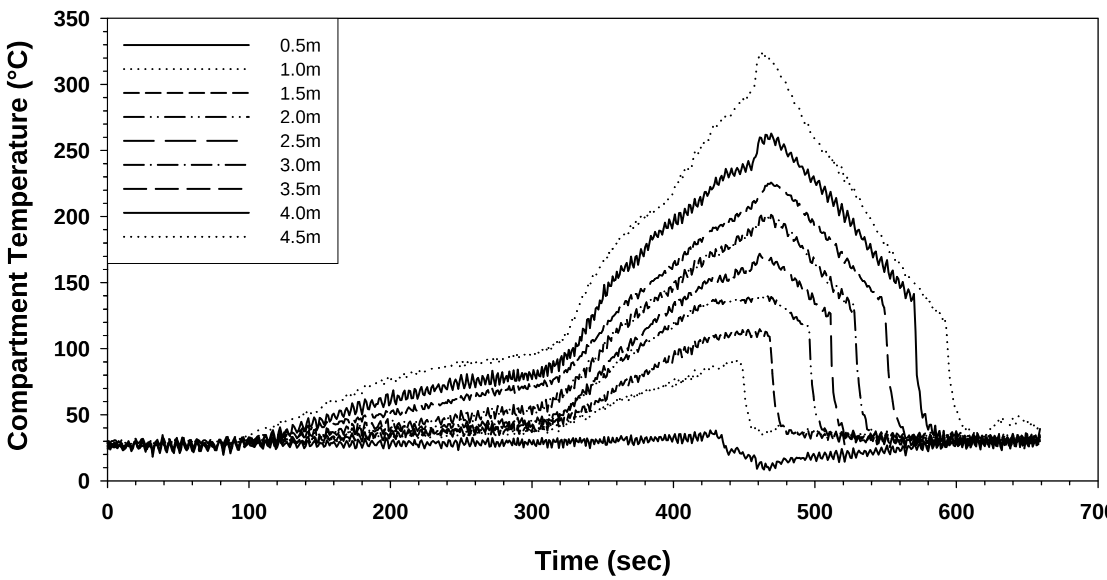
Chemguard Test 7 - Scenario 3



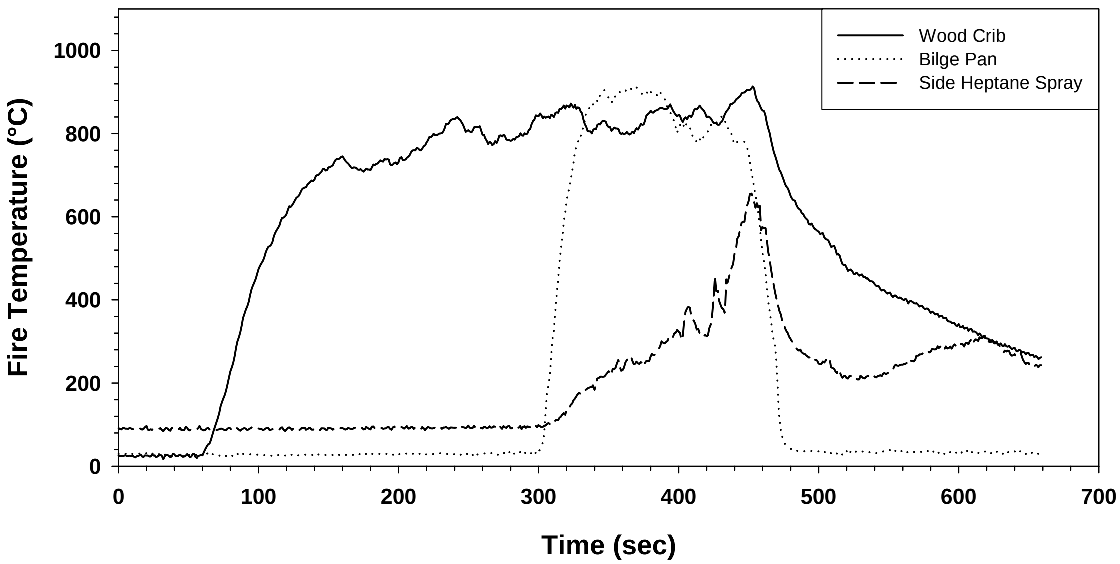
Chemguard Test 7 - Scenario 3



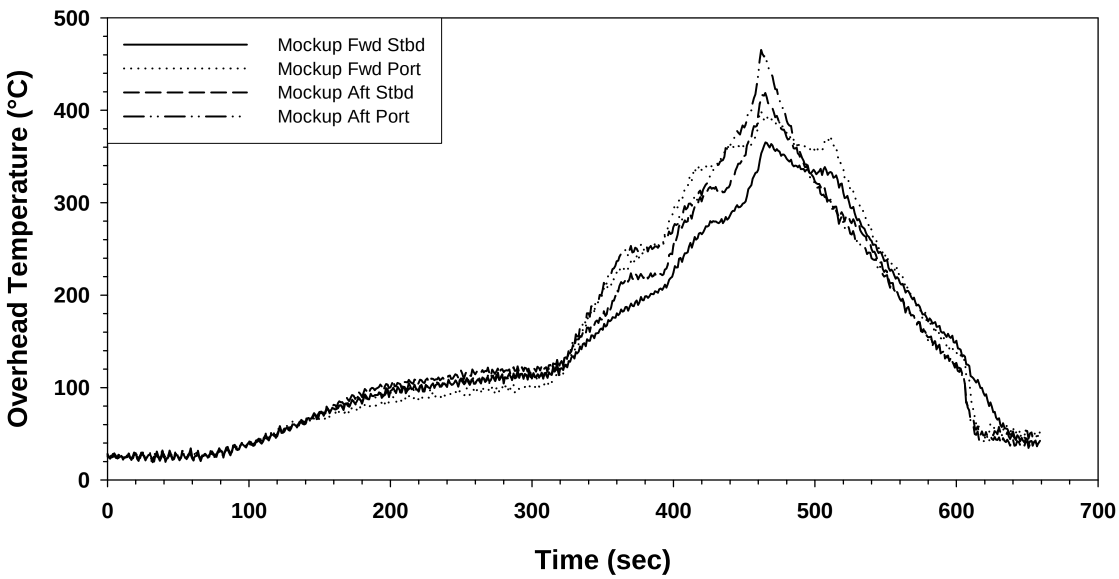
Chemguard Test 7 - Scenario 3



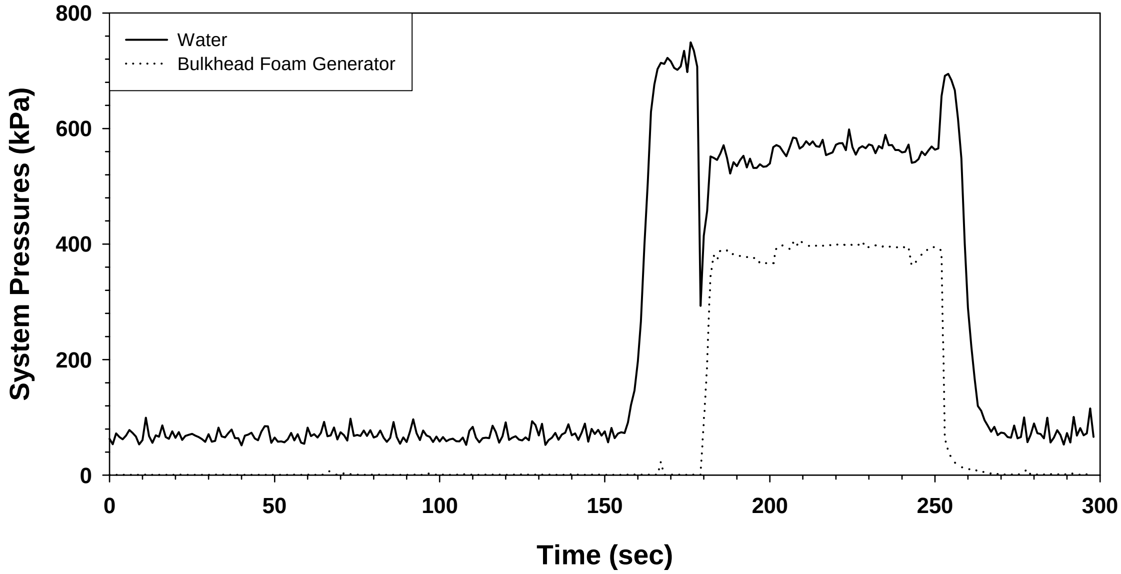
Chemguard Test 7 - Scenario 3



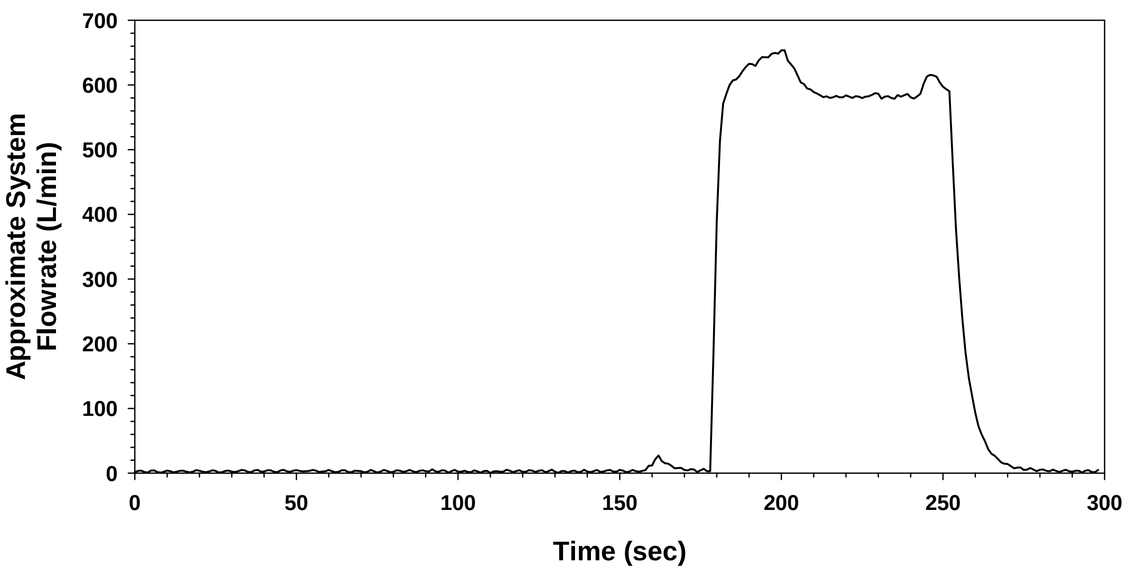
Chemguard Test 7 - Scenario 3



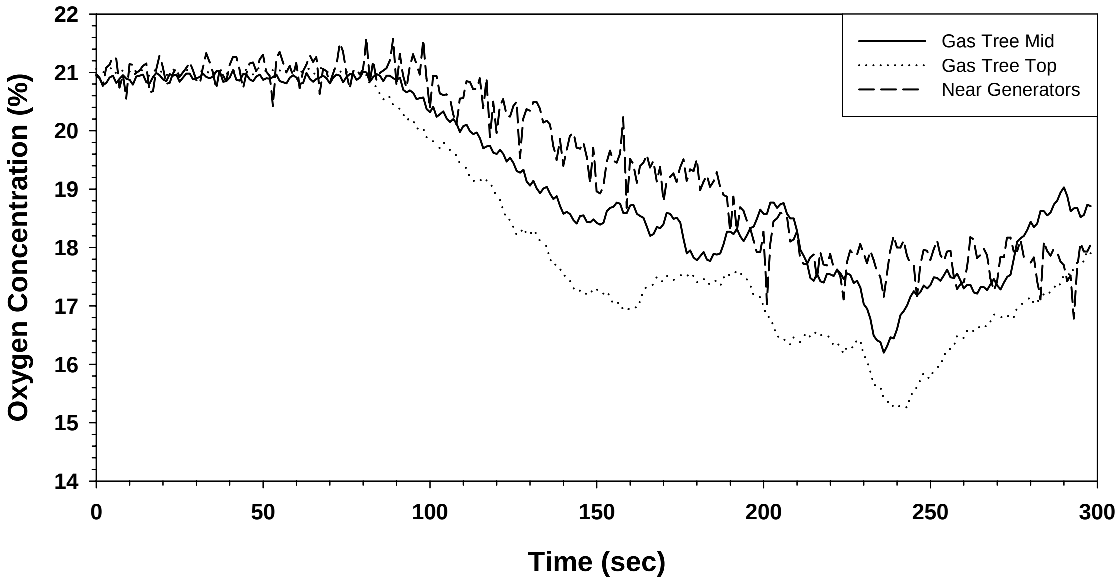
Chemguard Test 8 - Scenario 4



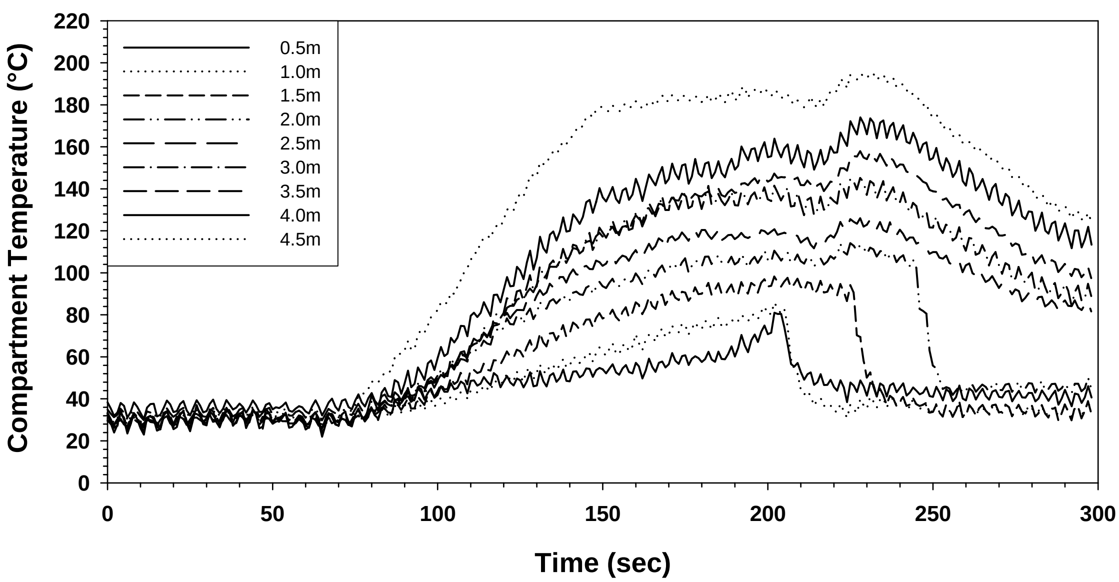
Chemguard Test 8 - Scenario 4

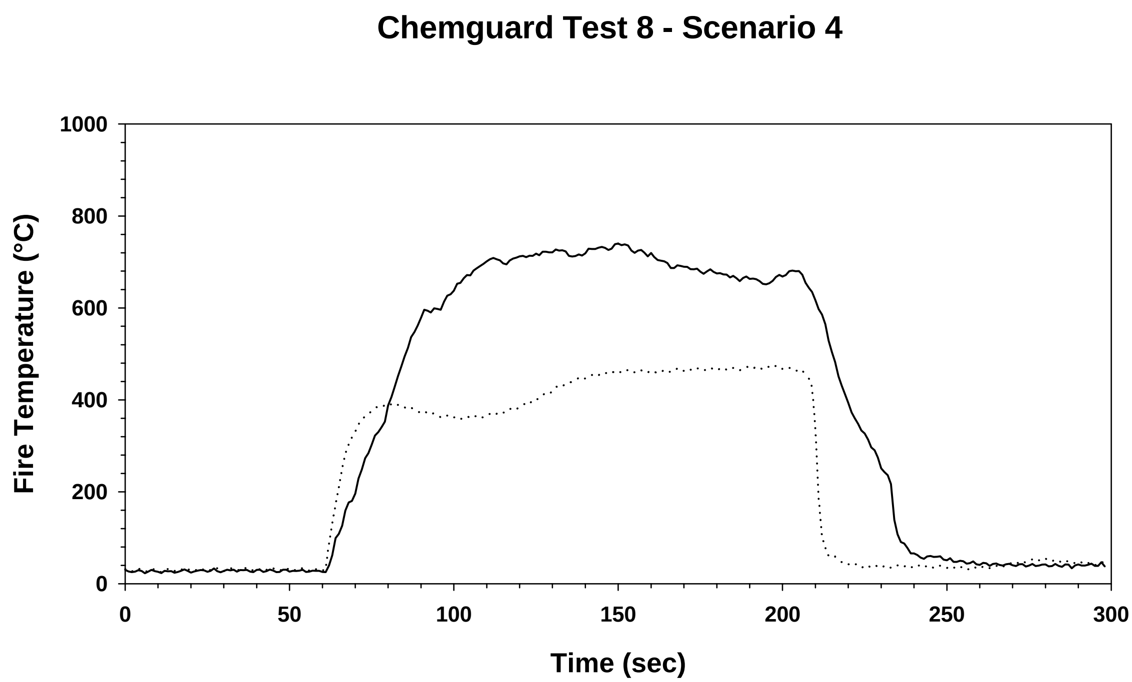


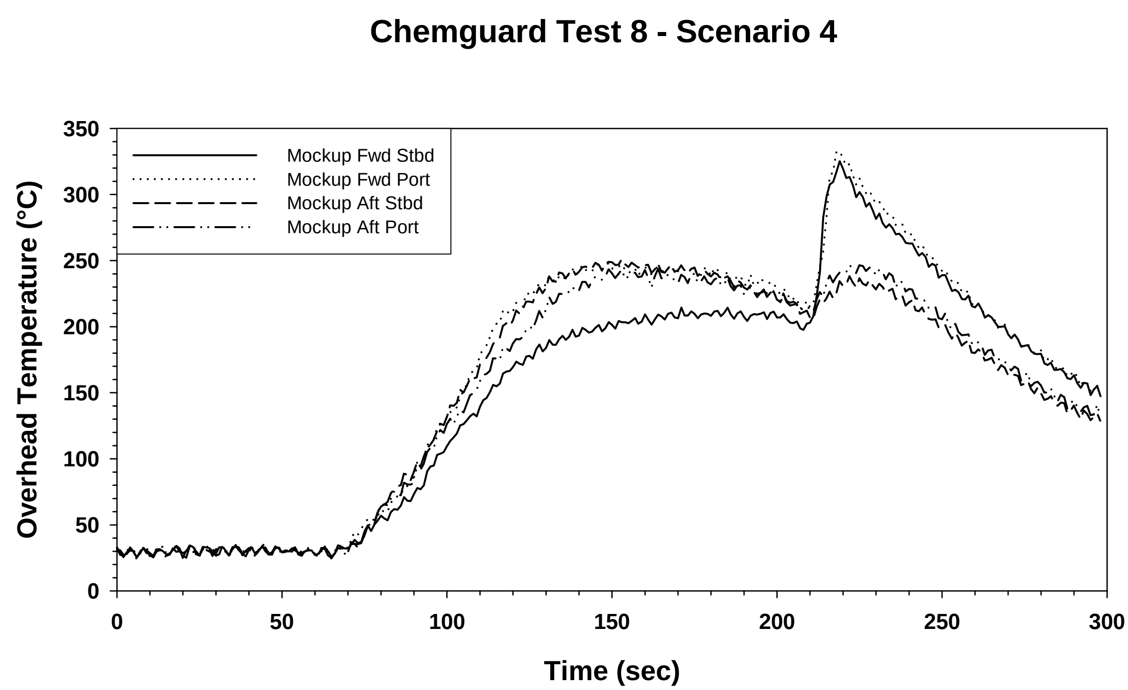
Chemguard Test 8 - Scenario 4



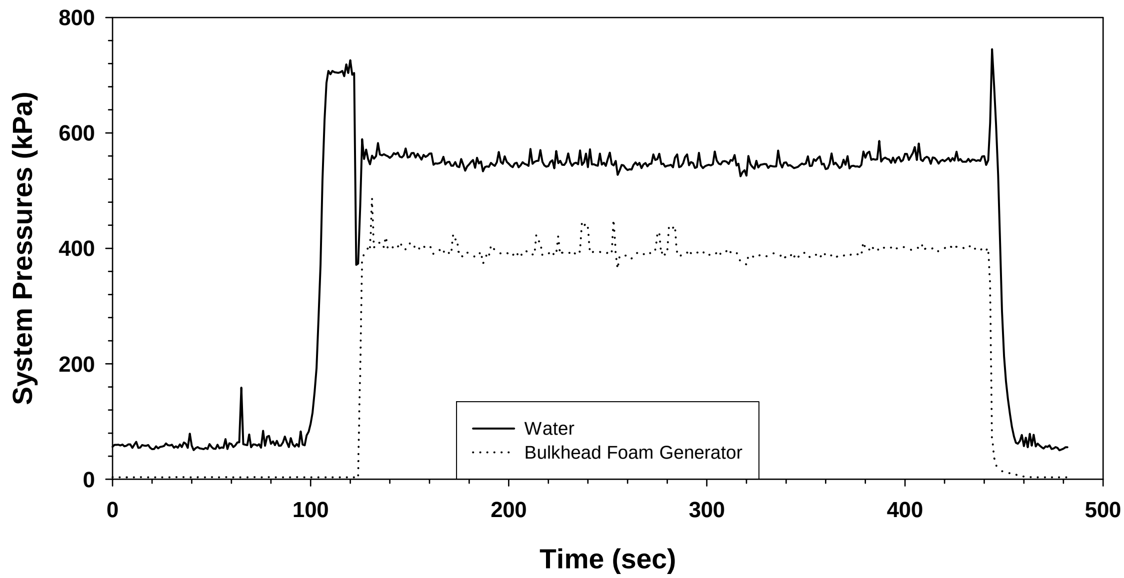
Chemguard Test 8 - Scenario 4



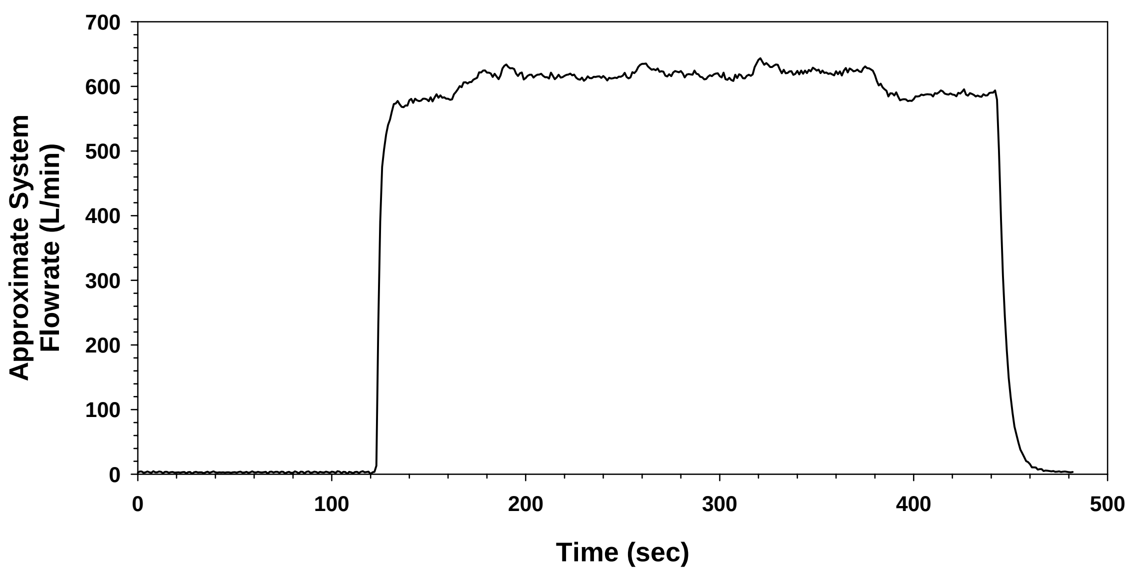

Chemguard Test 8 - Scenario 4
Fire Temperature (°C)
1000
800
600
400
200
0
0
50
100
150
200
250
300
Time (sec)


Chemguard Test 8 - Scenario 4
Mockup Fwd Stbd
Mockup Fwd Port
Mockup Aft Stbd
Mockup Aft Port
Overhead Temperature (°C)
350
300
250
200
150
100
50
0
0
50
100
150
200
250
300
Time (sec)

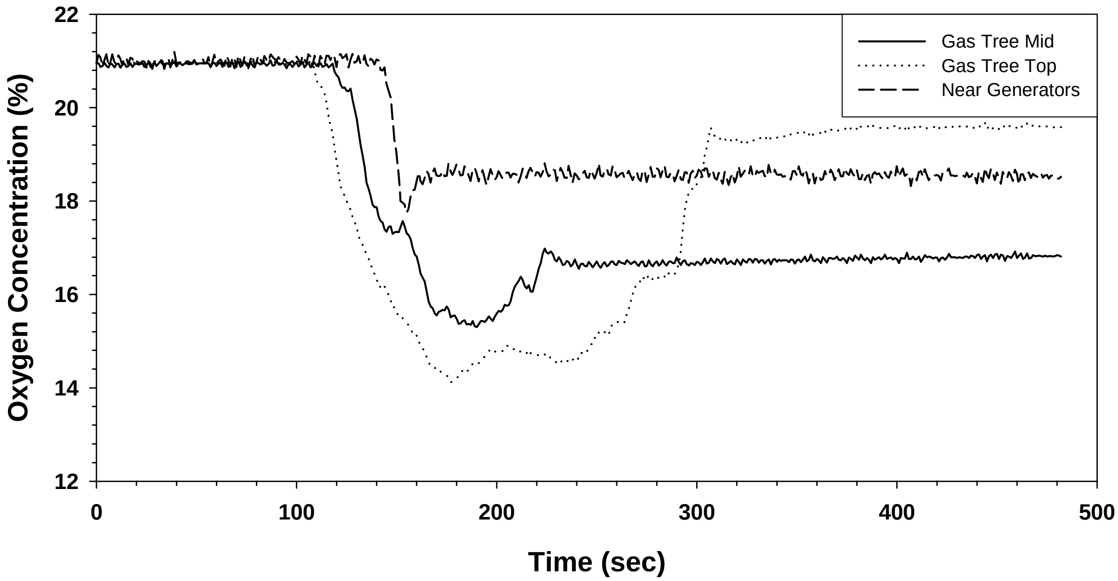
Chemguard Test 9 - Heptane Spray on Deck



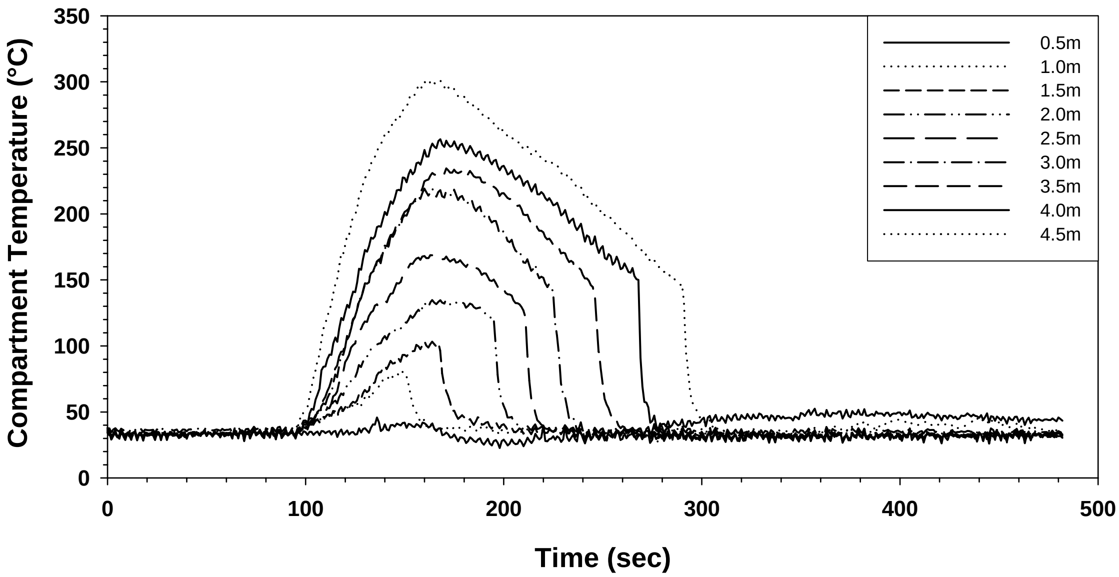
Chemguard Test 9 - Heptane Spray on Deck



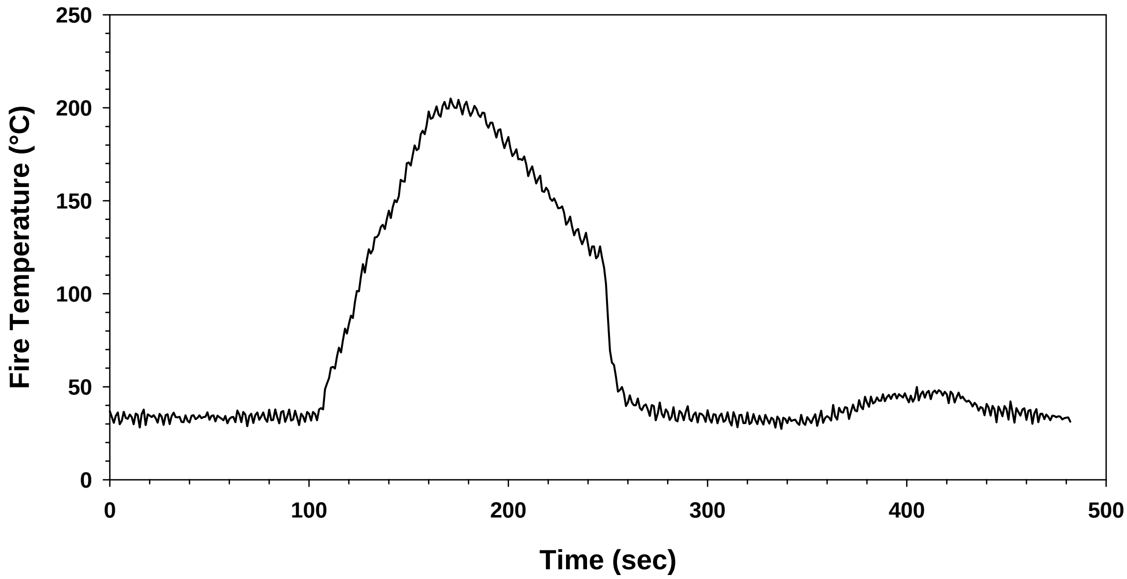
Chemguard Test 9 - Heptane Spray on Deck



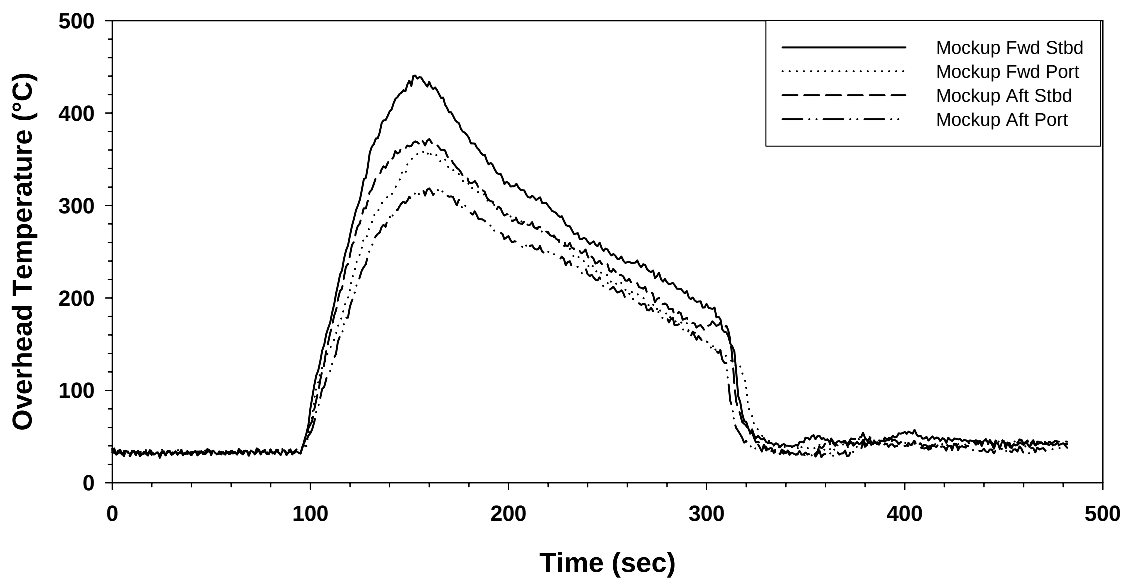
Chemguard Test 9 - Heptane Spray on Deck



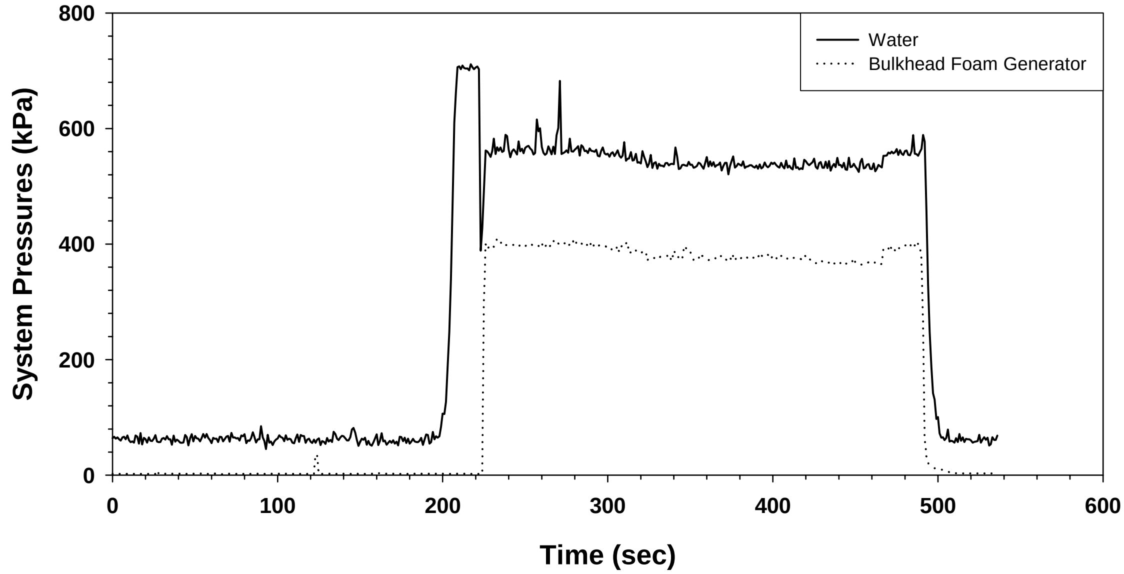
Chemguard Test 9 - Heptane Spray on Deck



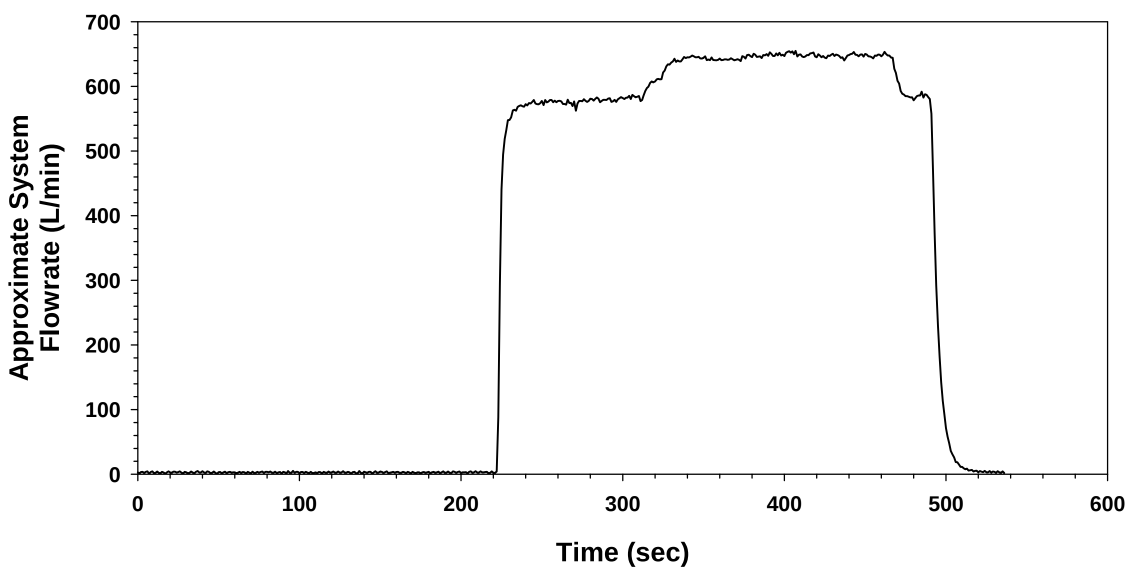
Chemguard Test 9 - Heptane Spray on Deck



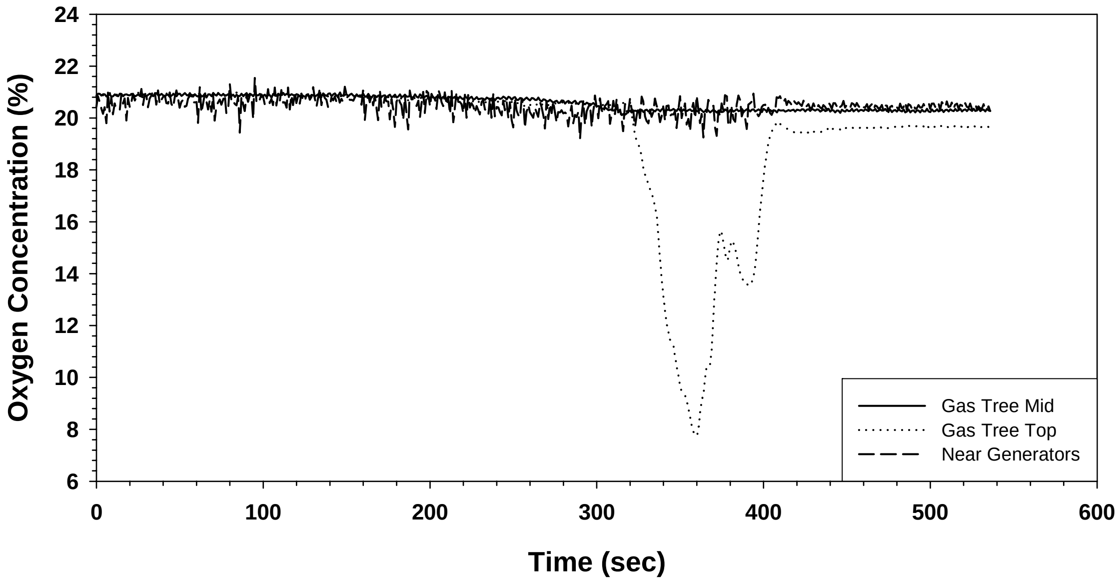
Chemguard Test 10 - Scenario 2



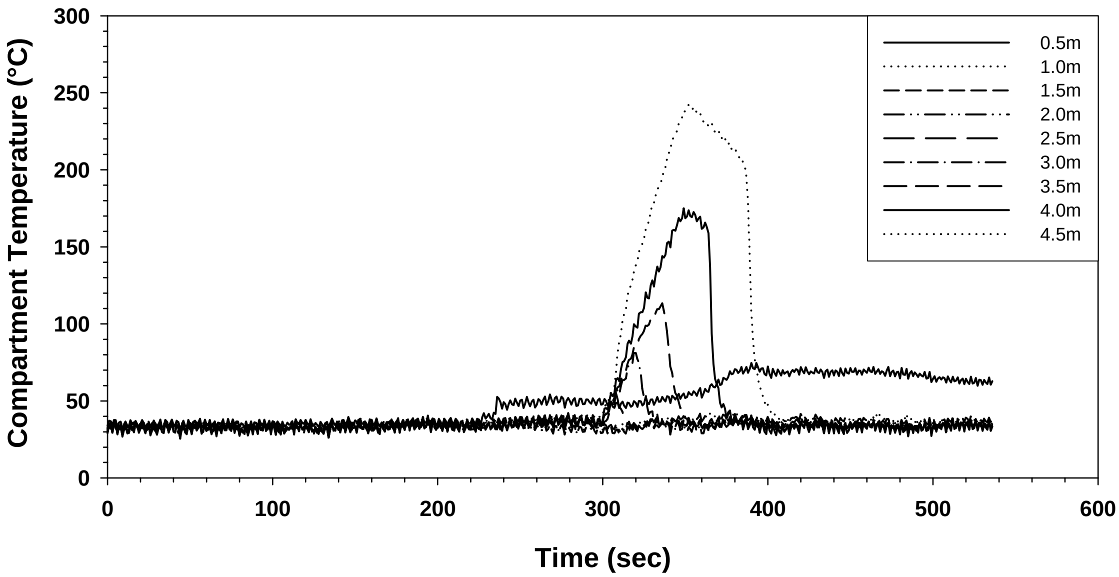
Chemguard Test 10 - Scenario 2



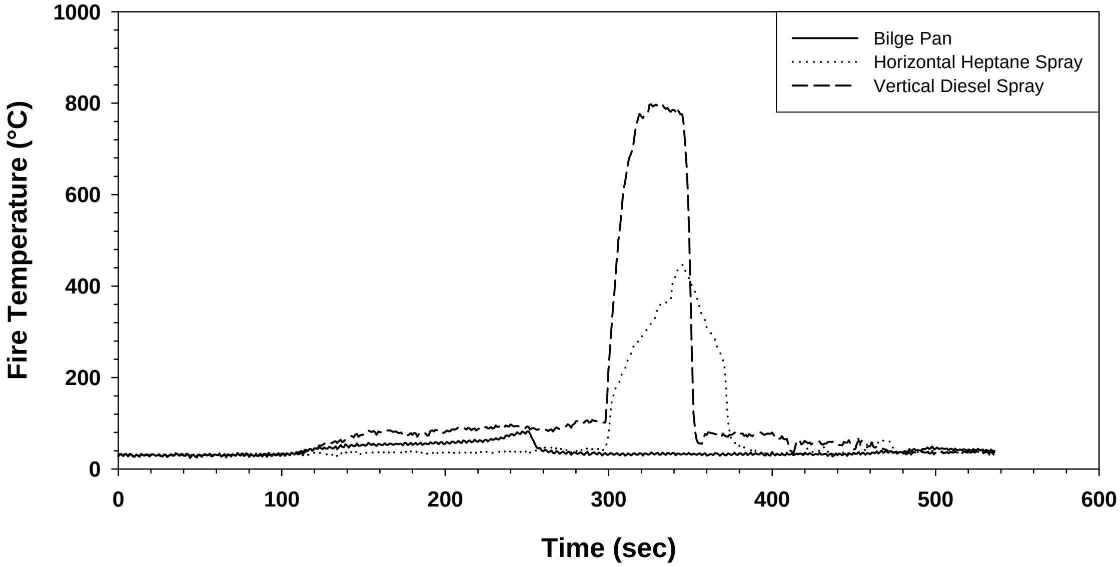
Chemguard Test 10 - Scenario 2



Chemguard Test 10 - Scenario 2



Chemguard Test 10 - Scenario 2



Chemguard Test 10 - Scenario 2